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Cleaner energy production by combined use of biomass plants and thermal plants: a novel approach for sustainable environment

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Abstract

Global research studies focus on cleaner bioenergy production by using biomass. Rice husk is one of the potential biomass resources for producing a significant amount of bioenergy. However, rice mills lack cogeneration facilities. Insufficient rice husk availability and accessibility data is another hindrance. As rice husk is abundant in rural areas and most of the rice mills are running on a small-scale budget, the establishment of new, highly equipped, expensive cogeneration facilities at all rice mills is not feasible. Instead, employing nearby sugar refineries and coal-fired thermal stations is cost-effective. Thus, this study examines the synergistic use of sugar refineries and thermal plants to produce rice husk-based cleaner energy. This study also proposes locations for new biomass-based power plants where sugar refineries/thermal stations cannot be utilized. The study focused on three major rice-producing states of India: Karnataka, Tamil Nadu, and Andhra Pradesh. 74 regions across three states were assessed. ArcGIS and multi-criteria-decision-making were used to analyze site suitability. Suitability values were tested for strength and reliability using sensitivity analysis. Analysis suggests the use of existing 44 sugar refineries and 7 coal-fired thermal stations for bioenergy generation. With this synergistic cleaner production technique, only 15 new rice husk-based power plants are required, and there is no need to construct at all rice mills. The rice husk from the study areas has the potential to produce bioenergy of about 466 MW. Thus, a 98.7% decrease in carbon emissions was seen when rice husk was utilized for cleaner bioenergy production instead of coal.

Keywords Rice husk, Sustainability, Cleaner energy, Sensitivity analysis, Circular economy

1 Introduction

The demand for energy on a global scale is consistently rising year after year due to the growth of the world's population and the expansion of the economy. The world population growth has led to a substantial 69.2% rise in energy consumption between 1990 and 2020 [1]. The electricity generation sector alone contributes to 70% of the total energy demand, especially in developing countries. Most of the energy demand is fulfilled by fossil fuel generation, which cause the climate crisis and other severe environmental impacts on human health and living conditions. Therefore, sustainable alternative energy resources are urgently needed in the global energy system for low carbon intensive energy supply. Thus, in 2015 all the countries in the United Nations adopted Sustainable development Goals (SDG). Out 17 SDG's, goal 7 signifies affordable and clean energy [2]. Therefore, the United Nations is currently prioritising the acceleration of the transition to affordable, reliable, and sustainable energy systems by utilizing renewable energy resources such as biomass. Hence, giving priority to energy-efficient techniques and embracing cleaner energy production such as bioenergy is crucial.

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India has experienced a significant increase in the energy consumption over the past three decades. India has become the third highest in the world in annual CO_2 emissions due to surge in the fossil energy consumption [3]. With a population of 1.4 billion, India has a massive demand for energy. Based on the sustainable development goals, India's power generation sector is rapidly shifting towards a more significant share of renewable energy like bioenergy. It is interesting to note that, India is also the world's third largest producer of renewable energy. Because 43% of installed electricity capacity in India comes from non-fossil fuel sources such as wind energy, biomass, solar and hydropower. The share of wind energy, bio energy and solar energy in renewable energy are about 32.0, 7.6, and 57.0% respectively [4]. India, being an agriculturally rich country, possesses huge quantities of agro-waste. Some agricultural waste, such as rice husk, rice straw, and sugarcane bagasse, has good calorific value, making them potential renewable resources for cleaner power generation. Hence, significant potential for biomass-based electricity generation in India is witnessed. Furthermore, the Ministry of New and Renewable Energy has undertaken steps to establish a waste-to-energy initiative as part of the National Bioenergy scheme for the period of 2021–2026. (Phase I) [5]. India is the world's second-largest producer of rice; it also generates large quantities of rice husk [6]. Hence, there is an increasing emphasis on utilizing rice husk as a sustainable energy source for generating power. A major barrier in the production of bioenergy from rice husks is the exorbitant cost involved in building new cogeneration facilities at rice mills. Consequently, despite the presence of a significant amount of rice husk and rice straw, their utilization as biomass is hampered due to the non-existence of cogeneration facilities. Therefore, paddy waste (consisting of rice husk and rice straw) was incinerated in the field as a means of disposal. This results in a decrease in soil fertility and an increase in emission of greenhouse gases, leading to climatic change as well as detrimental effects on the environment. At the same time, the construction of cogeneration facilities at all rice mills is very expensive and small-scale rice mills cannot afford highly equipped cogeneration plants. Alternatively, there are several sugar refineries and coal-fired thermal stations (thermal plants) are available in the regions of paddy cultivation. Hence, these sugar refineries and thermal plants can be utilized as cogeneration facilities for rice husk-based biomass. It leads to avoiding the construction of cogeneration facilities at each rice mill. It means that rice husk can be used in the adjacent sugar refineries or power plants and only a few new rice husk-based power plant facilities can be constructed where no sugar refineries/thermal plants are available. Hence, the current study focuses on possible use of rice husk in already existing plants as a primary objective. Moreover, identifying and proposing a suitable location for the establishment of only a few new biomass-fired power plants is also addressed where synergistic utilization is not preferred. Thus, the present study aims to use rice husk as a biomass resource for sustainable energy production by synergistically using the existing sugar refineries and coal-fired thermal stations, along with the proposed new biomass-fired power plants.

The Southern region of India is known for its diverse rice varieties and significant contributions to India's overall rice production. Karnataka state exhibits a wide range of agro-climatic zones, encompassing both coastal regions and the Deccan Plateau. The diverse climatic conditions of the state are favourable to cultivate a substantial quantity of paddy. Tamil Nadu state agro-climatic conditions, including its hot and humid climate, makes it more suitable for rice cultivation. Andhra Pradesh state is renowned as the Rice Bowl of India because of the existence of major river basins. This state alone contributes to 12.2% of the rice production in India. Hence, the three major and large states of southern India, namely: Karnataka state, Tamil Nadu state and Andhra Pradesh state, were considered for the study. A total of 118 sugar refineries and 21 coal-fired thermal stations from all the three states were considered for the synergistic utilization. The multicriterial decision making approach and ArcGIS were utilized in a methodological framework to determine the best suitable place for the construction of new biomass-fired power plants. Additionally, the viability and stability of the proposed suitable locations for the construction of new biomass-fired power plants were evaluated by performing a sensitivity analysis. Furthermore, the study also examines the utilization of the existing biomass for the purpose of cogeneration in the facilities that are already in place for cogeneration in coal-fired thermal stations and sugar industrial facilities.

2 Rice husk for cleaner energy: availability and challenges

Sugar mills do not have a consistent supply of sugarcane bagasse throughout the year. The duration for harvesting the sugarcane crop ranges from a minimum of one year to eighteen months, depending upon whether it is cultivated in tropical or subtropical locations. The sugarcane harvest season typically occurs from December to March. In the study regions of Andhra Pradesh, Tamil Nadu, and Karnataka states, rice is cultivated during all seasons. The duration required to harvest the paddy crop ranges from 105 to 150 days, with a maximum limit of 180 days from the time of sowing. This ensures a minimum of three crops every year, which signifies the availability of rice husk even in the sugarcane off-season. Hence, the seasonal variations of rice cultivation do not affect the stability of sugar mills for power generation. India possessed approximately 378.2 Bt of coal reserves as of 2019 [7]. Indian coal is distinguished by higher ash content and lower calorific value, rendering it a high-polluting energy source. To address the fundamental issues related to Indian coal use, the Central Electricity Authority of India has suggested a blending wherein 10–15% of the coal employed in power boilers is imported to enhance efficiency and reduce emissions. Despite its substantial availability, a shortage of coal is evident in India. For instance, In Punjab state, during the summer season, power demand increases by approximately 26%. This is due to elevated residential power consumption resulting from hot weather and heightened agricultural power demand due to paddy sowing. The state experiences a power deficit due to the unavailability of coal to satisfy the increased demand. In these cases, rice husks, which are abundantly available and possess biomass potential, can be utilized for cogeneration in existing coal-fired thermal power plants for energy production. Consequently, the suggested framework for the cogeneration of rice husk in sugar mills and coal-fired thermal stations remains unaffected by the seasonal fluctuations of rice cultivation. Moreover, the implementation of rice husk cogeneration within existing facilities aids in the achievement of increased energy requirements.

The management of rice husk storage has emerged as a critical component due to the seasonal characteristics of agricultural crops, typically cultivated three or four times annually. Hence, the rice husk needs to be managed for its effective utilization. This involves understanding the parameters related to the rice husk collection, transportation, and storage process. Many studies have reported detailed descriptions of these parameters in terms of case studies. Often in India, rice husks are collected and frequently stored temporarily at mills. Proper storage is crucial to avoid problems such as spontaneous combustion and to preserve rice husk quality. It is advisable to utilize covered, well-ventilated storage facilities to safeguard the husks from moisture and environmental deterioration. Storing the husks in covered areas, such as warehouses, silos, or barns, to keep them away from externalities like moisture is recommended. Furthermore, covering with plastic sheets or tarpaulin covers is found to effectively preserve the quality of stored materials [8–10]. An organized storage system can preserve the quality of feedstock and ensure optimal energy output [11]. A study reported that the installation of aeration systems mitigates temperature gradients and moisture condensation and aids in the prevention of mold and pest infestation [12]. The allowable moisture content for efficient storage is reported to be around 15%. However, it may reach 20% for short durations at lower temperatures [10]. Avoiding direct contact between rice husk and the floor helps mitigate moisture fluctuations. This can be done by positioning the plastic or wooden pallets on the floor [9]. Thus, implementing quality control methods such as regular inspections and pest control techniques helps mitigate the risks associated with storage. The primary challenges to biomass adoption for its effective utilization are addressed through the establishment of an effective transportation framework. Rice husk has a low specific mass, lighter in weight hence increased costs per unit volume of the material transported. Utilizing compaction techniques to increase the density helps in reducing transportation costs. Biomass densification is the common compaction technique. Pelletizing or briquetting of biomass results in a density of up to ten times greater than that of the original material [13]. For instance, a study noted that briquettes manufactured at lower pressures of 30 to 60 MPa crumble easily, while those produced at higher pressures of 150 to 250 MPa remain compacted and durable [14]. Thus, increased density allows for greater biomass transfer within the same volume, hence reducing overall transportation expenses. Furthermore, densified biomass is more manageable and storable owing to its uniform shape and enhanced stability. Reduction in particulate emissions per unit volume of material transported is also the result of this processing. This is attributed to the enhanced bulk and energy density per unit volume of biomass.

The utilization of rice husks for bioenergy generation, especially via cogeneration plants in rural India, offers significant potential alongside considerable obstacles. Rice husk, a by-product of rice milling, represents a plentiful biomass resource; however, its potential for energy generation is constrained by various economic, technical, and logistical challenges, especially for small-scale rice mills. These challenges hinder the effective utilization of rice husk in the bioenergy production. The challenges associated with rice husk utilization for bioenergy production in rural regions of India are: High upfront costs: Establishing cogeneration facilities necessitates a considerable financial commitment for essential equipment, including boilers, turbines, and the infrastructure needed for energy conversion like energy grid system. Small and medium-sized rice mills, prevalent in rural India, face significant challenges to establish the new biomass-based energy generation plants due to high investment cost compared to their actual turnover. Although government initiatives such as the National Bio-Energy Mission offer certain incentives, they frequently extend funding for the large-scale biomass plants and merely consider small and medium scale rice mills which are mostly located in rural India. Limited profitability in small mills: A significant number of rural rice mills in India function with narrow profit margins, which complicates their ability to rationalize long-term investments for bioenergy generation. The upfront financial investment, along with ongoing maintenance expenses, diminishes economic viability. Furthermore, rural operators might not experience prompt economic benefits, which could hinder their willingness to establish new biomass-based power generation unit in their rice mills. Logistical barriers: Rice husk is light in weight, and hence bulky in nature. It adversely affects transportation cost-associated with rice husk. As a result, less quantity of rice husk can be transported in the standard vehicle size compared to the conventional coal and other biomass materials. In fact, high quantities of rice husk are required for bioenergy production, and hence, the transportation cost per ton of rice husk is higher. The low density of rice husks presents a significant logistical challenge for handling and transportation.

Challenges associated with storage: As rice husk is bulky in nature due to its less density, the large storage space is essential for handling and storing the rice husk biomass. However, small and medium sized rice mills face challenges to store rice husk and hesitant to reuse it in bioenergy generation. As a result, these small and medium scale rice mills prefer to dispose rice husk as a waste in rural regions instead of using as biomass. Inconsistent availability of rice husk: Variations in rice production with respect to seasons results in inconsistent availability of rice husk. Small-scale rice mills face challenges in obtaining rice husk during non-harvest periods, which could further restrict energy production throughout the year. This inconsistency in the availability of rice husk is one of the major constraints for small and medium scale rice mills for the establishment of full-scale bioenergy production units. Policy barriers: Although there are various incentives for adopting renewable energy, including subsidies and tariff policies, these incentives often lack consistency and are fragmented across various states. This introduces ambiguity for individual investors operating on a smaller scale. Furthermore, the unwillingness to invest in the rural sector also hinders the efficient use of rice husk. Lack of infrastructure and skilled technician: A significant number of rural rice mills do not have access to advanced technologies that can effectively utilize rice husks for energy production. Moreover, operating and maintaining cogeneration systems necessitates a high level of technical expertise. In rural India, small-scale rice mill owners frequently face challenges related to insufficient knowledge and limited access to skilled technicians.

India is projected to have a capacity of around 7000 MW of electricity generated from 650 sugar mills. Studies show that approximately 47% of sugar mills in India have implemented cogeneration facilities [15]. A study shows that the Indian sugar sector is currently adopting more efficient cogeneration and combined heat and power systems, which is anticipated to improve the sector's sustainability in the near future. Andhra Pradesh, Maharashtra, Karnataka, Uttar Pradesh, and Tamil Nadu have been leading the way in the implementation of cogeneration [16]. Hence, the recommended study areas for synergistic utilization provide the potential for cogeneration. Furthermore, utilization of biomass also aids in environmental advantage due to reduced emissions. Additionally, the implementation of pollution control measures, such as electrostatic precipitators, flue gas desulfurization units, and baghouse filter technologies, leads to a decrease in particulate matter, SO_x and NO_x emissions [17, 18]. Facilities utilizing advanced pollution prevention technologies demonstrate enhanced efficacy in reducing emissions. The compatibility of the existing boilers represents a crucial factor for biomass cogeneration. The compatibility of boilers for cogeneration in sugar mills depends on the type of boiler, the fuel used, and its efficiency [19]. Nonetheless, integrating pre-treatment systems for rice husk, such as drying and size reduction or modifications to combustion chambers, contributes to improved energy efficiency. Rice husk is incinerated independently in sugar mills and thermal power plants. Rice husk and sugarcane bagasse are biomasses derived from agricultural waste. Therefore, the setup of cogeneration boilers in sugar mills is compatible with rice husk-based biomass. Because of this, investigating the feasibility of utilizing locally accessible biomass resources in the cogeneration of boilers of sugar mills which are already in operation is crucial.

In the case of thermal plants, the cogeneration capacity of boilers is well-above the capacity needed for biomass like rice husk. This is due to the fact that the combustion temperature of biomass is lower than that of coal. It is interesting to note that the existing cogeneration systems in sugar mills and thermal plants has provision to regulate the temperature at a precise level and attain the required temperature with respect to any type of biomass. As a result, locally accessible biomass resources such as rice husk can be employed with current infrastructure. Additionally, the non-availability of sugarcane bagasse throughout the year is another underlying issue of sugar mills that needs to be addressed. In such a sugarcane off-season period, these cogeneration boilers are not being utilized. Nevertheless, during this period of underutilization, there is an abundance of other alternative biomass resources that are already available and can be utilized with the existing facilities. In a similar way, one of the most significant challenges faced by developing nations in India is the limited availability of high-quality coal for the generation of power. As a result, thermal plants can utilize locally available biomass resources like rice husk in scenarios where quality coal supplies are limited. Considering the limited availability of sugarcane bagasse and the restricted supply of coal year-round, this study aims to explore alternative biomass sources that could be utilized for cogeneration.

3 Methodology

The study utilizes a multicriteria decision-making procedure and sensitivity analysis to determine the most suitable locations for the new biomass-fired power plants. The adopted methodology is illustrated in Fig. 1. The approach consists of five distinct stages: Stage 1: Selection of study area and criteria; Stage 2: Data collection and processing; Stage 3: Criteria weightage determination using Analytical Hierarchy Process (AHP); Stage 4: Computation of suitability index (SI_n); and Stage 5: Sensitivity analysis.

3.1 Stage 1: Selection of study area and criteria

India is an agriculturally rich country. As the economy of the country is rapidly increasing, the demand for power is following a rising trend. Thus, the electricity generation from biomass, particularly rice husk, aids in fulfilling the demand for power supply in an environmentally friendly manner. Rice in the Southern region is mainly produced in the deltaic regions of the Godavari River, Krishna River, and Cauvery River. The southern part of India is rich in paddy cultivation, hence three major rice-producing states, namely, Karnataka (state 1), Tamil Nadu (state 2), and Andhra Pradesh (state 3) are considered for the analysis. Rice from Paddy cultivation not only serves as a staple food crop, but the residue rice husk acts as a potential biomass for power generation. The representation of geographical areas with the codes assigned to the districts in the three states under consideration were depicted pictorially in Fig. 2. The criteria considered for the study are identified based on the experts' opinions and comprehensive literature reviews [20–23]. The primary aim was considered as effective valorisation of rice husk for clean bioenergy. In addition to the rice husk-based bio-plants, the possibility of using adjacent existing cogeneration facilities was also investigated. The criteria considered for the study were determined by also considering the already existing power plant facilities like sugar refineries (SR) with cogeneration facilities and coal-fired thermal stations (CT) that are suitable for cofiring. In this way, effective utilization of paddy waste can be achieved. Even though biomass feedstock availability is a prerequisite, it is not the only criterion required to find a suitable location for the construction of new biomass-fired power plants. The other key indicators were determined to be the proximity to the pre-existing cogeneration facilities, such as SR and CT in the same region.

While proposing the construction of a new power plant, it is also essential to incorporate elements grounded in social and economic considerations. Population density is one such crucial socioeconomic factor. India is a nation rich in agricultural resources, with the majority of its inhabitants living in rural areas.

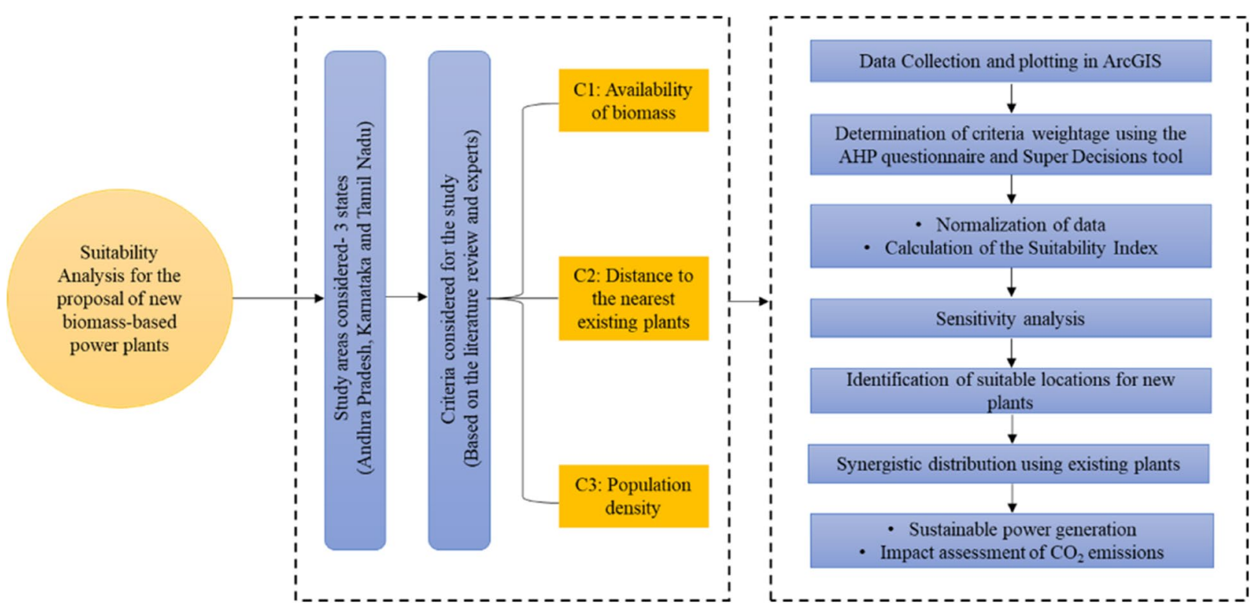

Fig. 1 Methodology adopted for the current study

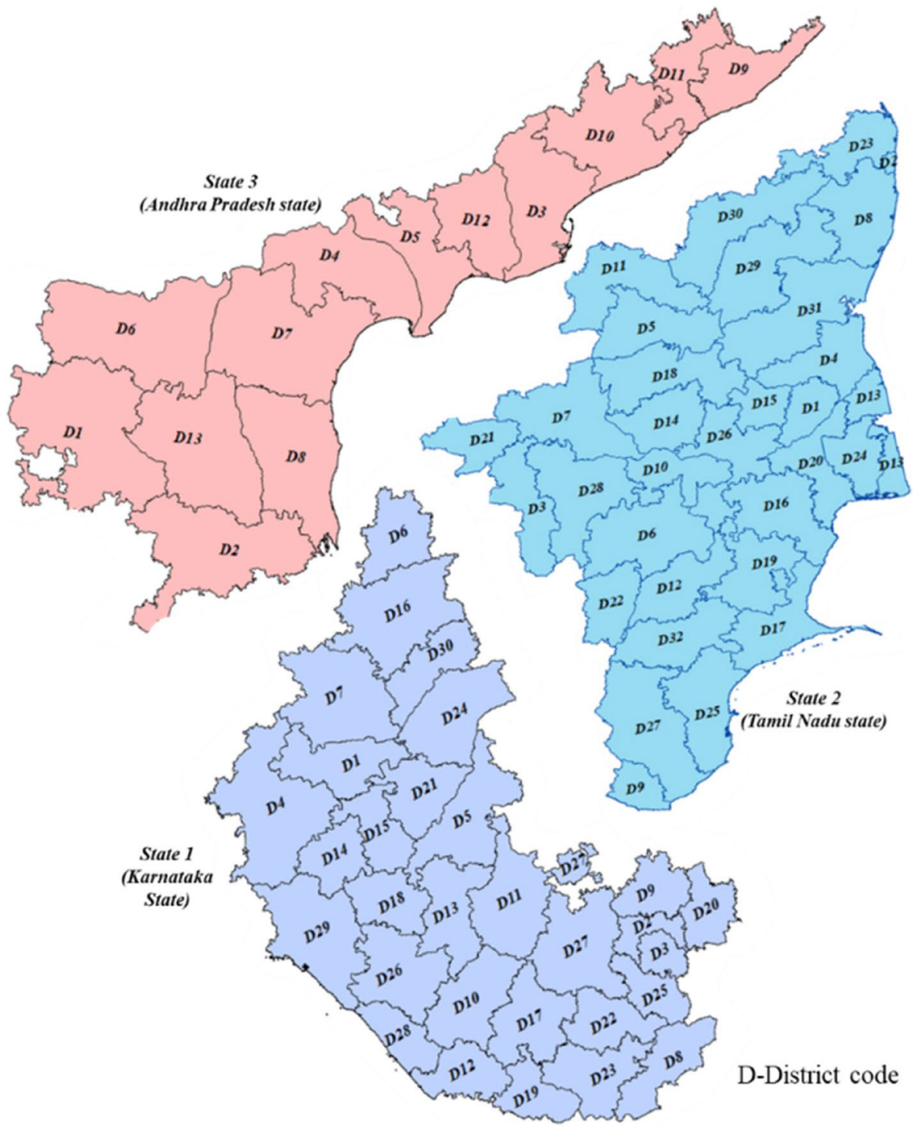

Fig. 2 Representation of the geographical regions with assigned district codes for the three states considered in the study

Nonetheless, the government still in the process of achieving to meet the energy needs in many rural regions for both residential and commercial use. This is because of the scarcity of non-renewable resources, namely coal, and the centralized distribution of thermal power plants. Consequently, the establishment of the proposed biomass power plants that utilize readily available agricultural waste in communities for energy production aids in fulfilling the energy needs of adjacent villages. Moreover, the energy produced from biomass is significantly more sustainable from both economic and environmental perspectives. Additionally, it promotes a rural-centric economy by creating employment opportunities that encompass plant operations, maintenance, and the collecting and transportation of biomass. This mitigates rural unemployment. Hence, it is essential to identify a suitable site for establishing a new biomass power facility. Furthermore, the Indian government has introduced numerous schemes and policies, such as the National Rural Electrification Policy, aimed at enhancing electricity generation, especially in rural areas, while prioritizing reliability, quality, and decentralized power distribution. Many studies have reported the importance of choosing population density as a socio-economic criterion for the suitability analysis of biomass plants. The size of the population measured in terms of its density are crucial elements that affect a region's appropriateness for biomass plant development.

The substantial population base and elevated growth rate contribute to a rapid increase in electricity consumption, which in turn propels the advancement of the energy sector [24]. According to Hiloidhari et al. (2017), population density is an important aspect to take into consideration to locate biomass power plants. This is because population density can have an effect on logistics, transportation costs, and potential environmental and social implications [25]. Population density serves as the criterion for distinguishing between centralized and distributed layouts [26]. The accessibility of biomass for energy will be affected by population growth [23]. Therefore, it is essential to regard criterion population density as one of the three major criteria. The density of the population plays a vital role in assessing the viability of a biomass power plant, impacting economic, social, and environmental factors. Areas with high population density frequently offer possibilities for addressing substantial energy needs and efficiently handling urban waste. Nonetheless, these regions encounter obstacles, including restricted land access, increased expenses, ecological issues, and possible opposition from localities. Conversely, areas with low population density in rural regions present a more favourable environment for biomass plants, owing to the accessibility of feedstock, decreased land expenses, and diminished social resistance. Nonetheless, these regions might experience reduced energy demand coupled with increased transmission expenses. To tackle these challenges, strategically positioning biomass plants, such as in proximity to agricultural areas with access to waste, can facilitate a balanced approach. Furthermore, decentralized, small-scale biomass power systems present a viable strategy for addressing energy requirements while reducing land disputes and environmental issues. It is imperative to note that the government of India gives several incentives to biomass power plants which supply biomass-based electricity to the adjacent electricity sub-stations. This electricity is directly used to fulfil the power requirement of rural regions. As a result, rice husk-based power plant get significant additional revenue through electricity generation. Therefore, rice mills located in the rural areas with high populations prefer for the establishment of new rice husk-based power plants owing to the high incentives from the government as well as additional revenue through electricity supply. Thus, integrating population density into suitability analysis enhances decision-making, optimizes resources, and promotes balanced growth.

Hence, the defined criteria are the quantity of biomass available, accessibility to the pre-existing SR as well as CT, and population density. C1- Quantity of biomass available; C2- Access distance to the closest existing SR/CT; C3- Population density. The present study involves taking rice husk as biomass, which has a high calorific value. Therefore, the terms biomass and rice husk will be used interchangeably in the subsequent sections.

3.2 Stage 2: Data collection and processing

The first stage of the present study entails the study area selection and finalizing the criteria. Afterwards, the second stage follows the collection of data related to the three criteria defined. The data related to criteria C1: the quantity of biomass available, C2: the access distance to the closest pre-existing SR/CT, C3: Population density, were collected for three states considered in the study. The quantified resources of biomass that are available in 30 districts (state 1- Karnataka state), 31 districts (state 2- Tamil Nadu state), and 13 districts (state 3- Andhra Pradesh state) were considered for the study [27]. The exact locations of the existing SR with cogeneration facilities [28] were considered, and the same was meticulously plotted using ArcGIS. As a result, a total of 118 SR was considered for the study, with 28, 51, and 39 in the study areas of Andhra Pradesh state, Karnataka state, and Tamil Nadu state, respectively. Similarly, the precise geographic positions of the existing coal-fired power plants in three states were also taken into account [29]. Thus, a total of 21 coal-fired power plants from the three study areas were plotted. The latitude–longitude coordinates of all the existing SR/CT were double-checked and incorporated into the ArcGIS. Network analysis was performed to calculate the access distance to the closest existing SR/CT using ArcGIS as an interface. The population density statistics for the entire study region, which includes 3 states and 74 districts, were collected from the official census conducted by the Government of India [30]. It is necessary to process the data after the collection of the required data for the criteria considered for the study is done. The analysis has three diverse sets of input criteria that correlate to three separate measurement units. To make the data comparable, the data has to be normalized. Therefore, the data was standardized to produce a dimensionless score ranging from 0 to 1. Min–Max normalization technique was used for normalization. The data pertaining to all three criteria were normalized to the dimensionless score ranging from 0–1. The R-studio software was utilized as the interface. The representation of the normalized data for the criteria C1, C2, and C3 were shown in Fig. 3 for the three states considered in the study.

3.3 Stage 3: Criteria weightage determination using AHP

A survey of experts' opinions was done using a questionnaire form based on the Saaty scale. Nevertheless, the importance assigned to criteria differs among individuals. Therefore, The AHP was used to determine

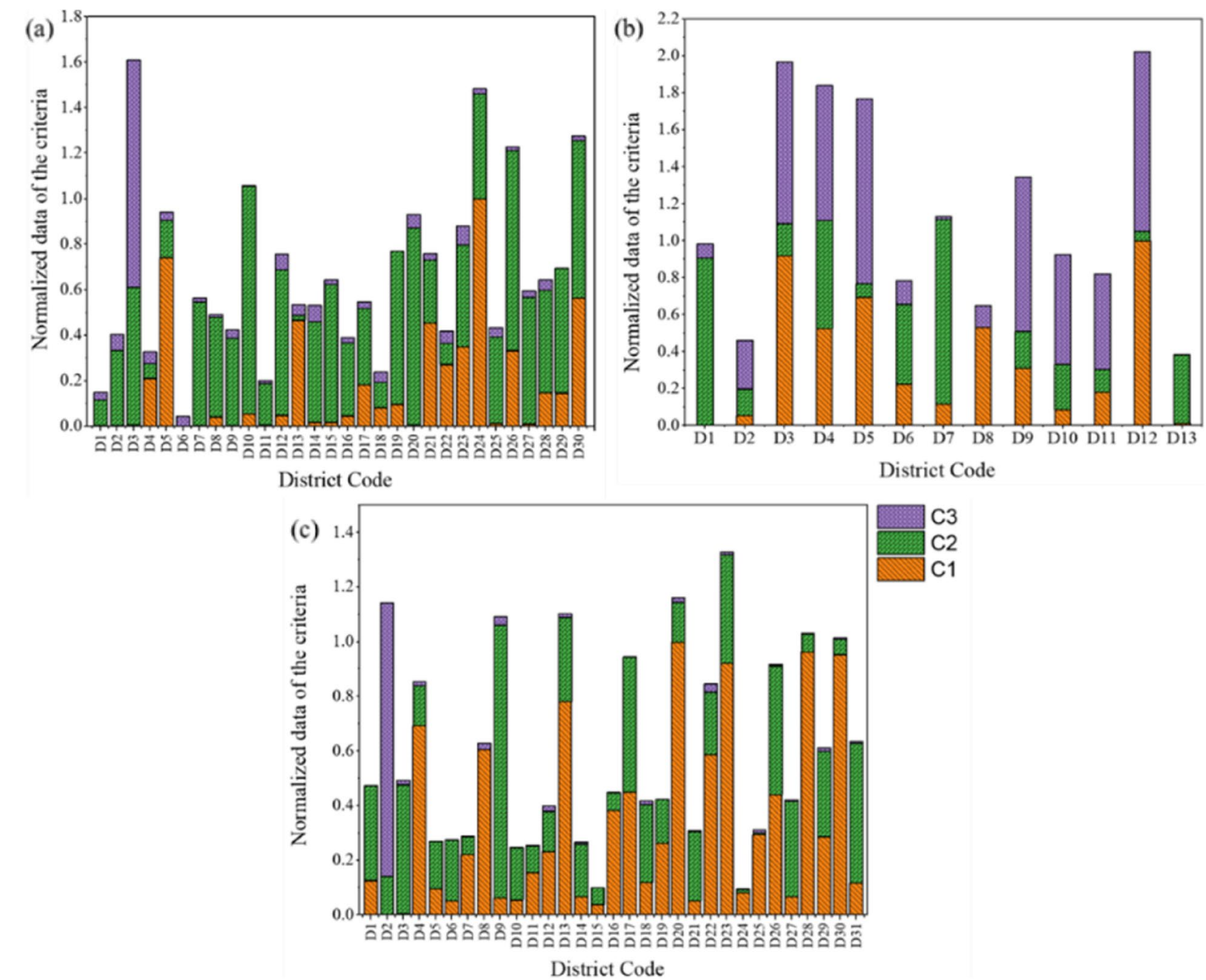

Fig. 3 Normalized data representation of C1, C2 and C3 criterion for three states (**a**) Karnataka state (**b**) Andhra Pradesh state and (**c**) Tamil Nadu state

the significance of the criteria in terms of its weightage. The present study sought evaluations from industry and academic professionals specialising in biomass-based energy generation, sustainable renewable resources, and multi-criteria decision-making (MCDM). These evaluations were subsequently utilized to establish the weightage of criteria. The experts' judgements were obtained by a pairwise assessment of the criteria C1, C2, and C3, which were evaluated on Saaty's fundamental scale, ranging from 1 to 9. The replies from the experts were further examined and combined to determine the weight of each and every criterion using the Super Decisions tool.

3.4 Stage 4: Computation of SI_n

A SI_n is a quantitative measure used to assess the appropriateness of different locations for a specific purpose or activity. It is commonly used in geographic information systems (GIS) to guide in decision-making processes related to land use planning, site selection for new plants, resource allocation to the demand points like biomass supply to power plants, and other spatially relevant applications [31, 32]. This study utilized the integration of GIS with MCDM approach to establish decision-making choices in a systemic framework. It offers a direct method for assessing decision-making situations regarding the setting up of new biomass-fired power facilities. The SI_n facilitates the assessment of different alternatives by considering multiple factors to ascertain the most appropriate option. The purpose of the SI_n in this study is to assess the possibilities based on defined criteria (C1, C2, and C3) and examine the alternatives (3 states—74 districts) to determine the most appropriate and suitable location for new biomass-fired power facilities. By using the weighted linear combination methodology, the

SI_n values were determined [22]. Accordingly, the current study computed the SI_n values in the range of 0–100. Equation (1) was utilized to obtain the SI_n.

$$SI_n = \sum_{m=1}^{3} W_m Y_{mn} \tag{1}$$

where, SI_n = Suitability index value of the nth district; W_m = Weightage assigned to the mth criteria; Y_{mn} = Value of the normalized mth criterion for the nth district.

The SI_n was calculated for each and every district within the study areas 1. Karnataka state (30 districts), 2. Tamil Nadu state (31 districts), and 3. Andhra Pradesh state (13 districts). The greater the SI_n score, the more suitable it is. As a result, the districts were assessed and evaluated to ascertain the feasibility of constructing new cogeneration facilities or optimizing the use of SR/CT for the cogeneration of paddy waste based on their SI_n values. The proposed new biomass power plants for each state are represented as KB, TB, and AB for Karnataka, Tamil Nadu and Andhra Pradesh states respectively.

3.5 Stage 5: Sensitivity analysis

The current study uses sensitivity analysis, a methodical strategy to assess the extent to which changes in input parameters may be attributed to variations in the output of a model or system. when proposing the location for the setting up of a new power plant that utilizes paddy waste as a biomass resource, it is crucial to validate the location suitability values derived from the suitability analysis. This validation of the obtained suitability values is done by the utilization of sensitivity analysis. It entails analysing the effects of variations in input criteria on the output, thereby contributing to the understanding of the robustness and reliability of the suitability of the location under different scenarios. It is advantageous to examine scenarios where altering one single parameter impacts the suitability of the location for establishing the biomass-fired power plant. The aim of this sensitivity analysis is to identify the key input parameter/criteria that significantly influence the location suitability of the districts. The present study employed a one-at-a-time sensitivity analysis method, where each input criterion was individually modified [33]. The sensitivity analysis studies examine the impact of the input criterion C1, C2, and C3 on the SI_n value, which serves as the output. Each study area is assessed for its reliability to the SI_n values calculated in the previous section (stage 4). Therefore, a total of 74 districts from the entire three study regions can be considered as alternatives. To perform sensitivity analysis, the initial weightages of the criteria calculated are varied for different proportions separately. The weightage of the criteria C1, C2, and C3 is assessed individually for eight possibilities, notably ± 25%, ± 50%, ± 75%, and ± 100%. The criteria that are varied are termed subject criteria. The weightage of each criterion (C1/C2/C3) is changed for eight scenarios, and the respective variations in the criteria weightages are calculated as follows:

$$\mathrm{W} = \sum_{\mathrm{m}=1}^{3} \mathrm{W_m}]_{\mathrm{P_S}} = 1 \tag{2}$$

here S = Criterion index for which percentage change is applied, i.e., subjective criteria; $\mathrm{W_m}]_{\mathrm{P_S}}$= mth criterion weightage after the subject criteria's (S) percentage change; W = Summation of all criteria's weights.

The calculation of the subject criteria's weightage at a specific percentage change '$\mathrm{P_S}$' is performed as per Eq. (3).

$$\mathrm{W^S}\Big]_{\mathrm{P_S}} = \mathrm{W^S}\Big]_{\mathrm{P_S}=0} \times [1 + \mathrm{P_S}] \tag{3}$$

where $\mathrm{W^S}\big]_{\mathrm{P_S}=0}$ = weightage of subject criterion at zero percent change, i.e., the baseline weightage value of the criteria considered.

In a similar way, the weighting of the remaining criterion was proportionally adjusted, as delineated in Eq. 4, to satisfy the condition specified in Eq. (2).

$$\mathrm{W_m}]_{\mathrm{P_S}} = \left[\frac{1 - \mathrm{W^S}\big]_{\mathrm{P_S}}}{1 - \mathrm{W^S}\big]_{\mathrm{P_S}=0}}\right] (\mathrm{W_m}]_{\mathrm{P_S}=0}) \tag{4}$$

The sensitivity analysis examined three criteria and eight distinct scenarios of percentage change values, resulting in a total of 24 unique sets of criteria weightage values as outlined in Eq. 5.

$$\begin{bmatrix} \mathrm{C_1} \\ \mathrm{C_2} \\ \mathrm{C_3} \end{bmatrix}_{3\times1} \times \begin{bmatrix} \mathrm{P_{100}} & \mathrm{P_{75}} & \mathrm{P_{50}} & \mathrm{P_{25}} & \mathrm{P_{-25}} & \mathrm{P_{-50}} & \mathrm{P_{-75}} & \mathrm{P_{-100}} \end{bmatrix}_{1\times8} = \begin{bmatrix} \mathrm{W^1}\big]_{\mathrm{P_1}=100} & \mathrm{W^1}\big]_{\mathrm{P_1}=75} & \cdots & \mathrm{W^1}\big]_{\mathrm{P_1}=-100} \\ \mathrm{W^2}\big]_{\mathrm{P_2}=100} & \mathrm{W^2}\big]_{\mathrm{P_2}=75} & \cdots & \mathrm{W^2}\big]_{\mathrm{P_2}=-100} \\ \mathrm{W^3}\big]_{\mathrm{P_3}=100} & \mathrm{W^3}\big]_{\mathrm{P_3}=75} & \cdots & \mathrm{W^3}\big]_{\mathrm{P_3}=-100} \end{bmatrix}_{3\times8} \tag{5}$$

According to Eq. (2), for each percentage change in the subject criteria, the cumulative weights of the modified criteria should add up to one. The subject criteria influence on the variation of the other criteria weightages is calculated, and the corresponding varied criteria weightages are presented in Table 1. The criteria's respective shift in the SI_n for all accessible alternatives was calculated for all the study areas.

4 Results and discussions

In the current study, three different study areas, namely states 1, 2, and 3, were taken into consideration. The computation of the suitability values and the assessment of sensitivity analysis were carried out for all the states, taking into consideration each district as an individual location. This was done in accordance with the methodology that was stated in Sect. 2. The process of identifying the optimal location for establishing the new biomass-fired power facilities was assessed independently for the three study regions and results are discussed in the following sections.

4.1 Site suitability analysis

The Karnataka state comprises of 30 districts, with each district as one individual location for the suitability analysis. The higher the SI_n value, the greater the suitability. Thus, the suitability of a location for the proposal of new biomass-fired power plants increases as the suitability index value increases. As already mentioned, the study focuses on the synergistic utilization of existing plants; hence, the location suitability was proposed, keeping the constraint that there exists no SR/CT in the proposed districts. Figure 4 shows the SI_n value of each district from D1 to D30. District D24 has the highest SI_n, with a value of 62.9, while D6 has the lowest SI_n, with a value of 0.58. The higher index value of district D24 is attributed to the presence of abundant biomass, coupled with the absence of any nearby already existing SR/CT facilities. Nevertheless, in the case of district D6 has a limited amount of biomass resources available. Additionally, the already existing plants (SR/CT) are located within a 1.83 km radius. The average suitability index is found to be 27.3. Based on the descending order of the suitability values, 5 out of 30 districts were categorized to be most suitable for the construction of biomass-fired power plants. The proposed districts were chosen with the condition that no suitable district should contain any pre-existing cogeneration facilities. These districts are D30, D26, D10, D3, and D20, and the corresponding suitability index values are 55.1, 53.9, 47.5, 40.6, and 40.2. It is noteworthy that the five districts that were proposed have suitability index values higher than the mean suitability value of 27.3. Therefore, the identified five districts are highly ideal locations for the construction of new biomass-fired power plants. The districts D26 and D30 were identified as having the best suitability out of the top 10 districts due to their substantial availability of biomass. However, the suitability of the districts D3, D10 and D20 were attributed to the unavailability of already existing SR/CT in the vicinity.

Table 1 The weights of the C1, C2, and C3 criterion for each variation in percentage of the weights of the corresponding criteria

Criteria weightage	**100%**	**75%**	**50%**	**25%**
C1	0.834	0.730	0.626	0.521
C2	0.904	0.791	0.678	0.565
C3	0.261	0.229	0.196	0.163
Criteria weightage	**-100%**	**-75%**	**-50%**	**-25%**
C1	0.000	0.104	0.209	0.313
C2	0.000	0.113	0.226	0.339
C3	0.000	0.033	0.065	0.098

The state of Tamil Nadu (state 2) comprises of 31 districts as possible locations for the suitability analysis. The suitability index values of all the districts from D1 to D31 are depicted in Fig. 4. District D23 is determined to be the ideal location with the highest suitability value of 56.5, while district D24 is the lowest with a suitability value of 3.9. The higher the SI_n value, the greater the suitability. By considering the constraint that there should not be any pre-existing cogeneration facilities in the proposed locations, the most suitable five districts with high SI_n values were considered in the study. The mean suitability value of the state is 24.9. It is crucial to point out that 13 out of 31 districts have the potential for the construction of new biomass-fired power plants with a suitability value greater than the mean SI_n. The top 5 districts that are most suitable, based on their SI_n values, are D23, D9, D13, D17, and D26. These districts have SI_n values of 56.5, 48.2, 46.7, 41.2, and 39.8, respectively. The suitability of the districts D23 and D13 for constructing new biomass-fired power plants were attributed to the abundant availability of biomass. Additionally, the presence of ample biomass and the non-availability of the pre-existing SR/CT plants in the vicinity make the districts D17 and D26 more suitable. Although a little amount of biomass is available, in the case of district D9, the higher suitability can be ascribed to the non-existence of any pre-existing SR/CT facilities in the radius of 130 km.

The state of Andhra Pradesh consists of 13 districts. The district's suitability for establishing the new biomass-fired power plants is done by considering each district as one location. The SI_n values for each district were calculated as shown in Eq. (1). Figure 4 depicts the location SI_n values of all the districts of Andhra Pradesh state. The state of Andhra Pradesh is known as rice bowl of India, as it is a deltaic region with huge cultivation of paddy. Hence, all the districts in this state have almost ample amount of biomass available. Districts D4 and D2 have the greatest and the lowest suitability with the values of 57.9 and 12.1 correspondingly. The mean value for the

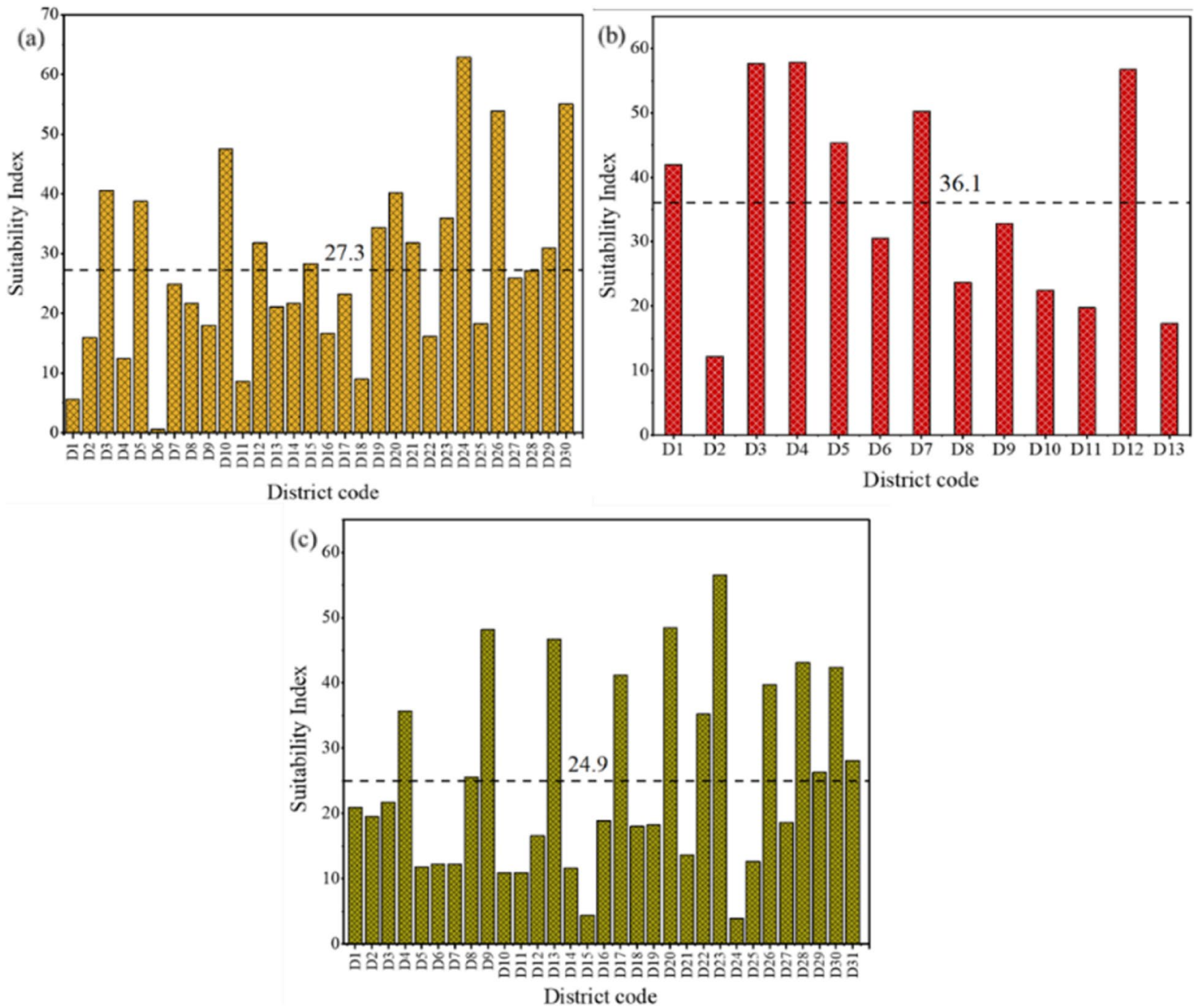

Fig. 4 Suitability Index for all districts in three states (**a**) Karnataka state (**b**) Andhra Pradesh state and (**c**) Tamil Nadu state included in the study

suitability of the location is 36.1. 6 out of 13 districts have the SI_n values greater than the mean value. D4, D3, D7, D1, and D9 are the top five suitable districts with suitability values of 57.9, 57.6, 50.3, 42.0, and 32.9, respectively. The districts D1, D4, and D7 were deemed most suitable due to the absence of any existing SR/CT plants within a radius range of 80–130 km. In contrast, the districts D3 has a preexisting SR/CT plant within a 30 km radius. However, the abundance of biomass in these districts makes them a more favourable location for establishing the biomass-fired power plants.

4.2 Sensitivity analysis

The suitability index was determined for eight different scenarios for the percentage change in the weightage of the criteria considered as described in Sect. 2 (stage 5). The depiction in Figs. 5, 6, and 7 shows how the SI_n values vary when the weights of criterion (C1, C2, and C3) change for the study area Karnataka state. Each district exhibits either a rising or falling trend in the SI_n when the percentage change of the criteria weightages decreases. When the weightage of C1 varies from 100 to -100%, all districts except D4, D5, D13, D21, D22, D24, and D30 show an upward trend in suitability of the location. The declining suitability can be attributed to the changes in the criteria respective to the availability of biomass in these locations. Therefore, if the weightage of the criterion C1 (biomass availability) is diminished, the suitability value will also fall. Similarly, when the weight assigned to criteria C2 is decreased, the SI_n values for the same districts were observed to increase. This is because the reduced weightage of C2 is reallocated to C1 and C3. These districts already have an adequate supply of biomass, and increasing the weightage further enhances their suitability for establishing new biomass plants. Once the criteria C3 weightage is reduced from

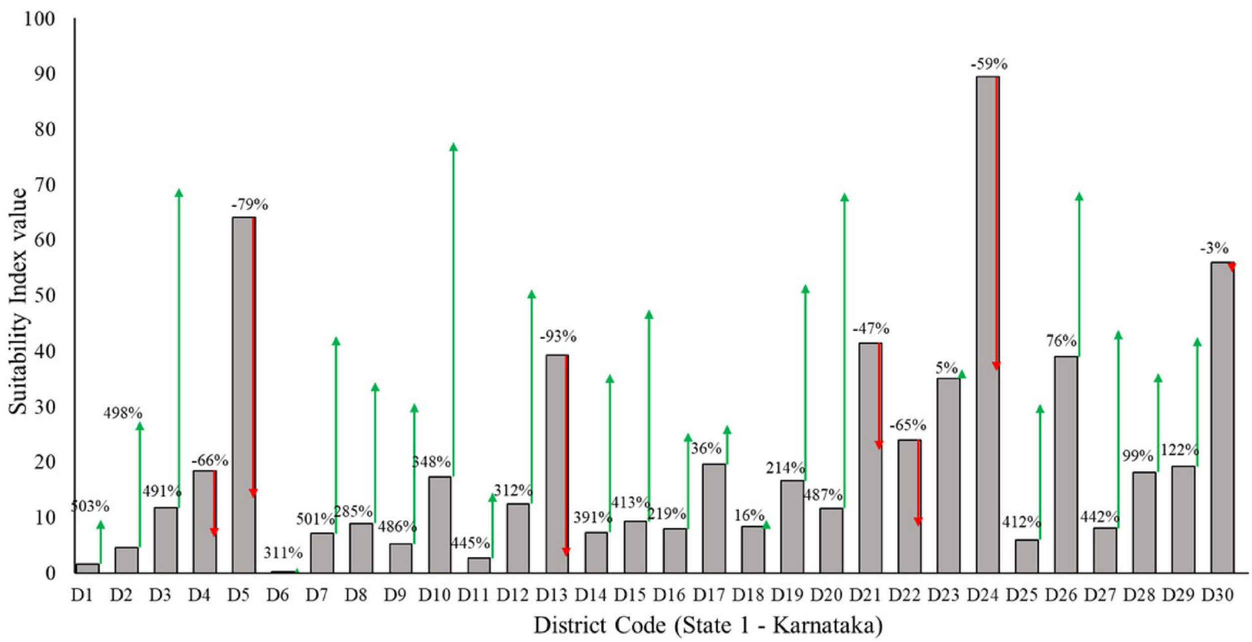

Fig. 5 Shift in suitability index for variation in criteria (C1) weightage from 100% to -100%

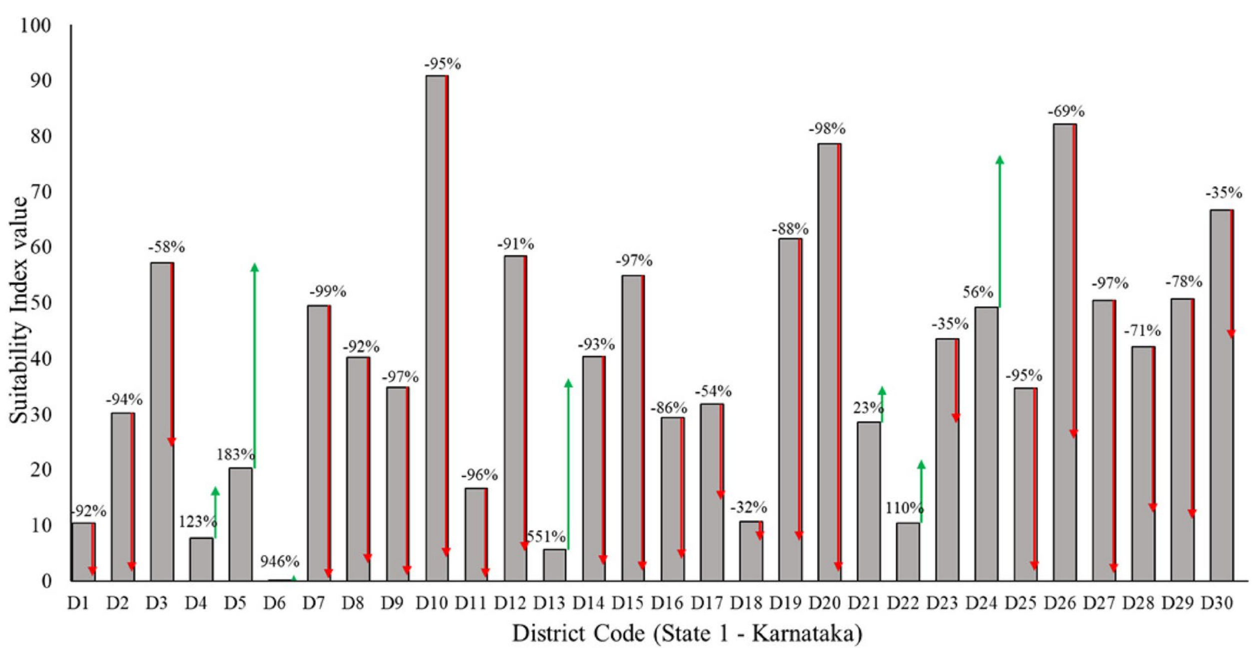

Fig. 6 Shift in suitability index for variation in criteria (C2) weightage from 100% to -100%

100% to -100%, the suitability values improve due to the increased weight of criteria C1 and C2. In the case of C3, the suitability values for the districts D3 and D6 exhibit a decreasing trend due to the extremely limited amount of biomass. Furthermore, already existing SR/CT plants are also found within a radius of 1.83 km for district D6, which diminishes its suitability as a potential location for establishing the new biomass-fired power plant.

The shift in the SI_n with the variation in the weights of the criteria C1, C2, and C3 for the study area Tamil Nadu state is shown in Figs. 8, 9, and 10, respectively. The trend of the suitability values variation exhibited an increasing or decreasing trend with the reduction in weightage

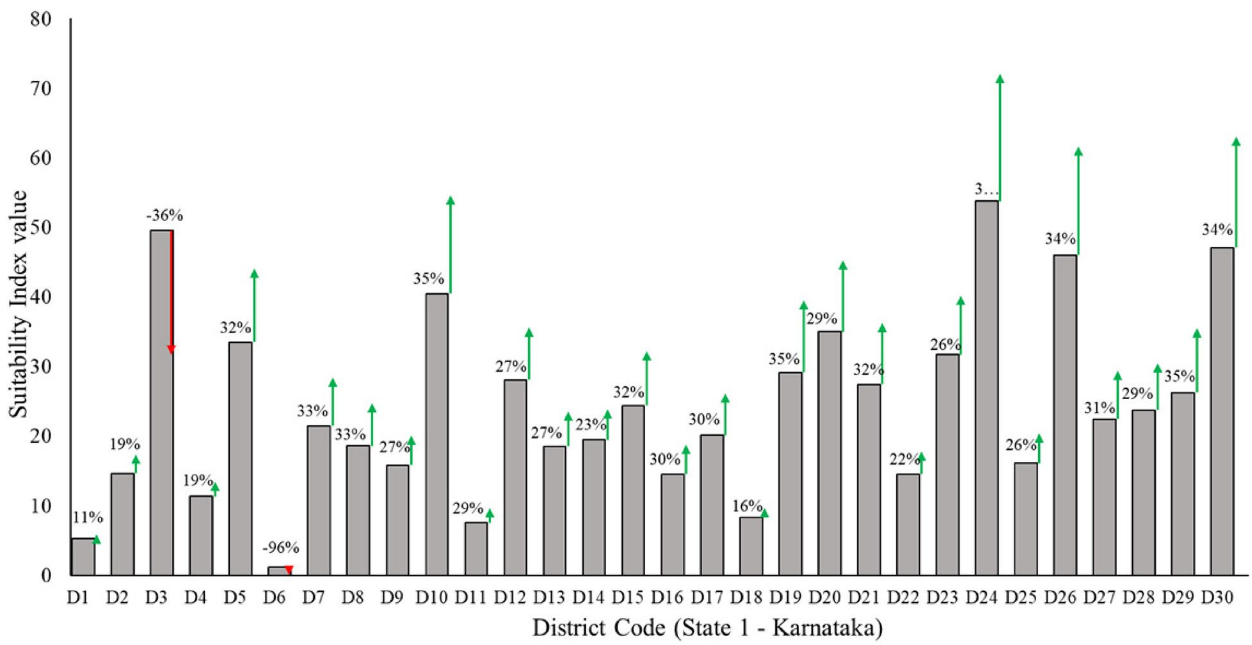

Fig. 7 Shift in suitability index for variation in criteria (C3) weightage from 100% to -100%

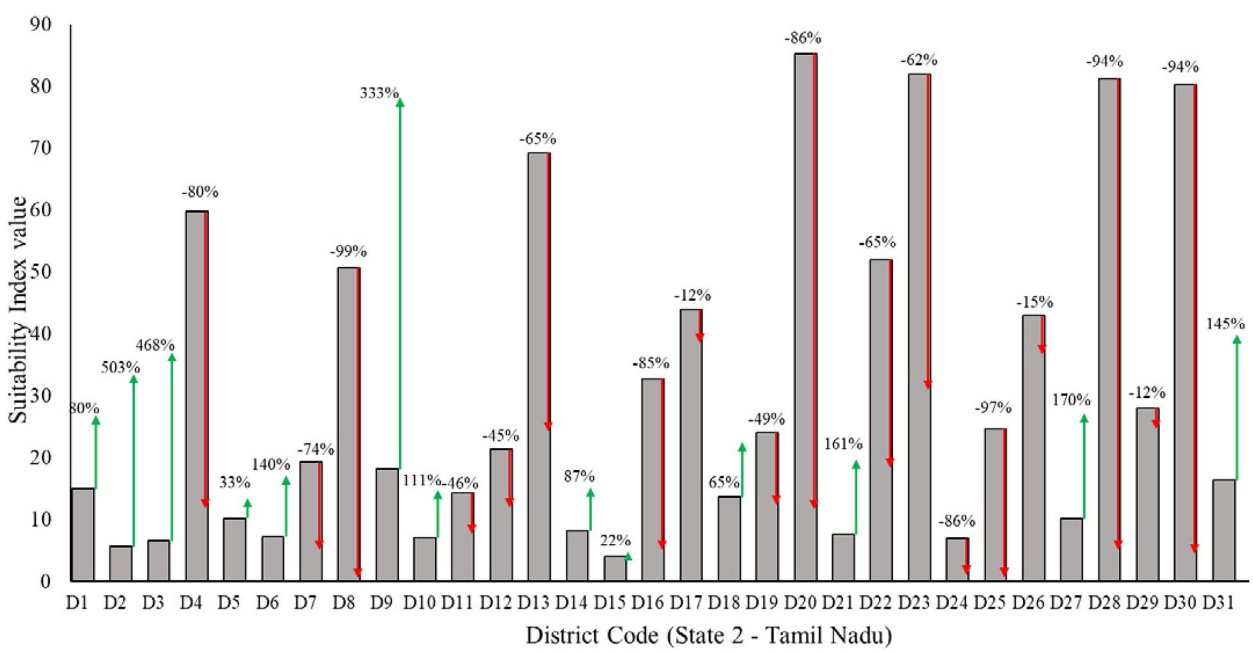

Fig. 8 Shift in suitability index for variation in criteria (C1) weightage from 100% to -100%

of the criterion from 100% to -100%. In the case of C1 criteria, the variation in the SI_n is found to follow both rising and declining trend. When the weightage of the criteria C1 is reduced, the increased weightage of C2 and C3 resulted in enhanced suitability in the districts where there is minimal availability of biomass without any already existing SR/CT plants in the vicinity. Thus, the increase in suitability is observed in the districts D1, D2, D3, D5, D6, D9, D10, D14, D15, D18, D21, D27 and D31 when the weightage of C1 is decreased. It is noteworthy that the location suitability values of districts D17, D26, and D29 follows a declining trend while the weights of

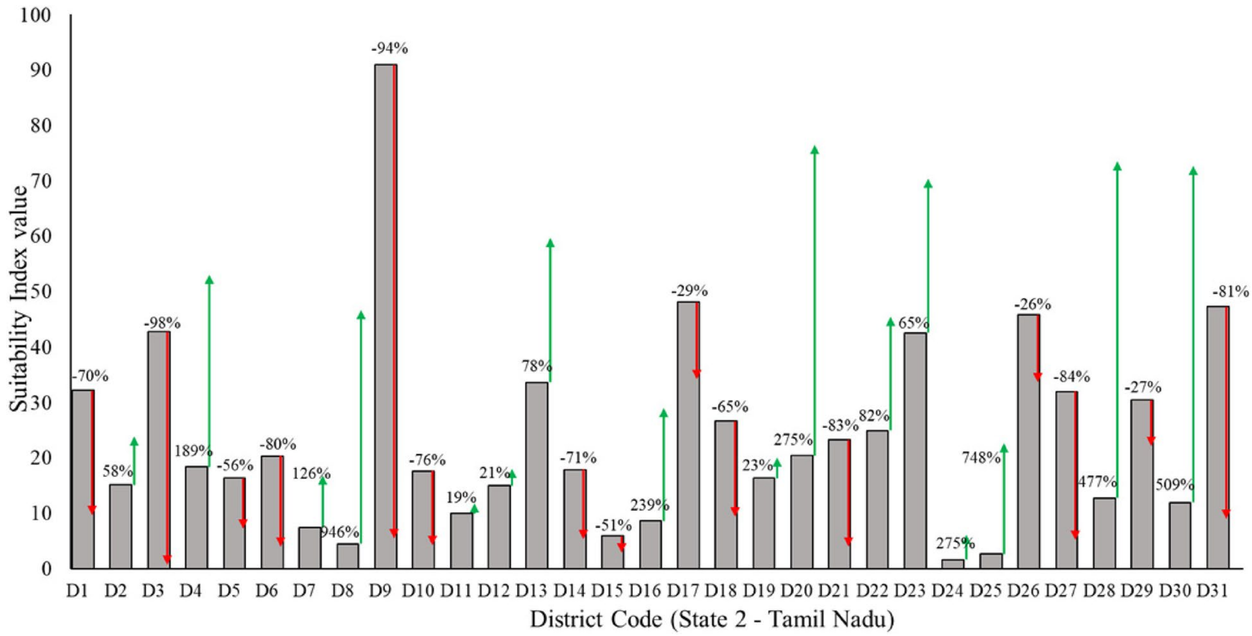

Fig. 9 Shift in suitability index for variation in criteria (C2) weightage from 100% to -100%

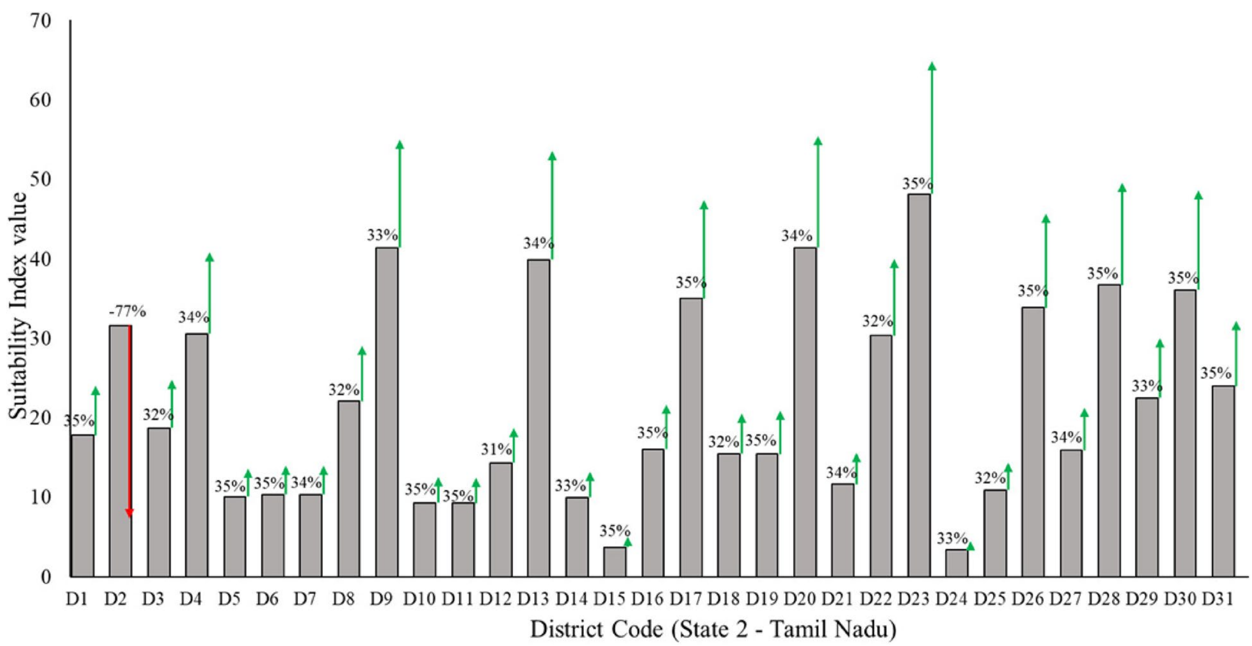

Fig. 10 Shift in suitability index for variation in criteria (C3) weightage from 100% to -100%

criteria C1 and C2 were individually reduced from 100% to -100%. Despite the availability of biomass in these districts, there exist SR/CT plants within a radius of 65, 64.9, and 45.2 km for districts D17, D26, and D29, respectively. Therefore, when the weightage of C1 is decreased, the redistributed weightage of C2 is enhanced. However, the presence of preexisting plants in these areas reduces its suitability for the construction of new biomass-fired power plants. For district D2, it observed that the suitability of the location is increased by about 503 and 58%, when the weights of the criteria C1 and C2 were reduced from 100% to -100% respectively. This is because, the district D2 is densely populated metropolitan region, with very minimal amount of biomass availability. Hence, the redistribution of the weightage to the criterion C2 and C3 resulted in such high enhanced suitability of the location. Regarding C3, apart from D2, which exhibits a high population density, all other districts displayed a noticeable upward trend in the suitability of their locations. This is because the weightage that was reduced is now applied to criterion C1 and C2, which are highly important for determining the adequacy of the location suitability for the establishment of new plants. Figures 8, 9, and 10 clearly demonstrate a significant disparity in the suitability of the locations in terms of SI_n values for criterion C1 and C2, compared to C3. The SI_n for all districts in C3 fluctuates within a range of 35%, but the upper limit of variance in suitability is significantly larger for C1 and C2, which demonstrates the significance of criterion C1 and C2 over C3.

When performed sensitivity analysis for the state of Andhra Pradesh, it is observed that SI_n variation follows a combination of an upward and downward trend, when the weights of the criteria C1, C2 and C3 were consecutively reduced from 100% to -100% as shown in Fig. 11. In the case of C1, the suitability of the districts D3, D5, D8 and D12 were found to be declined with a decline in the weightage of criteria C1. This is because these are the top districts in terms of the abundance biomass availability in the state of Andhra Pradesh. Moreover, these districts have already pre-existing SR/CT plant in the vicinity. Hence, the suitability of the location comes down. Similarly, in the case of C2, the suitability of the districts D3, D5, D8 and D12 were found to be increased when the weightage of the criteria is reduced due to excessive biomass. However, for the district D9 and D11, the suitability of the location is increased irrespective of the decrease in the weights of the criterion C1 and C2. This is attributable to the fact that districts have the ample amount of biomass with the preexisting plants in the vicinity. So, when one criteria weightage is reduced, the redistributed weightage to the C1 and C3 or C2 and C3 resulted in the increased suitability of the locations. This also implies that the criteria C3 is significant for these districts in terms of suitability of the location. When the criteria C3 weightage is decreased from 100% to -100%, the location suitability of the districts D1, D6, D7, D8 and D13 were found to be increased due to the reallocation of weightage to the criterion C1 and C2. It is also clearly noted from Fig. 11 that the difference in the variation of the suitability of the location is comparatively significant with criteria C1 and C2 than C3.

4.3 Comparative analysis

In the previous sections, the SI_n values and findings of sensitivity analysis were discussed individually for the three study areas considered. Now, in this section, the location suitability of the southern part of India (Karnataka state, Tamil Nadu state, and Andhra Pradesh state) as a whole was considered and discussed. District D23 of Tamil Nadu state was found to be highly suitable with a SI_n value of 56.5, followed by districts D30 (55.1) and D7 (50.3) of Tamil Nadu and Andhra Pradesh state, respectively. From the Figs. 5, 6, 7, 8, 9, 10, and 11, it can be inferred that SI_n values were more likely sensitive to the criteria C1 and C2, in comparison with C3. For the study area Karnataka state, the location suitability for the construction of new biomass-fired power plants were very sensitive to the criteria biomass availability, followed by the criteria C2. A similar pattern can be observed for the Tamil Nadu and Andhra Pradesh states. In the case of Karnataka state, the suitability of district D3 is observed to diminish by 58 and 36% as the weightage of criteria C2 and C3 is reduced from 100% to -100%, respectively. Nonetheless, an improved suitability exceeding 400% is observed in the instance of C1 variation. This can be explained by the high population density of the district and the restricted availability of biomass within the area. In a related observation, district D2, characterized by its high density in Tamil Nadu state, exhibits a 77% reduction in suitability when the weight of C3 is diminished. These regions benefit from robust infrastructure, such as well-developed road networks, which reduce transportation costs and enhance accessibility to the biomass. Although criteria C3 has a considerable effect on the location suitability for the construction of new plants, the sensitivity of criteria C3 is minimal when relatively compared with that of C1 and C2 in the states of Karnataka and Tamil Nadu. However, for Andhra Pradesh state the sensitivity of the criteria C3 for the location suitability is almost on par with that of the criteria C1 and C2, unlike the other two states. This is attributed to the fact that the state has all the districts moderately populated with a population density ranging from 213 to 518, unlike the huge difference in the range in Karnataka and Tamil Nadu states. The shift in the suitability values lies in the range of 8–40%, either following an increasing or decreasing trend. It implies that, for a given population density, the location suitability for establishing the new biomass-fired plants is highly influenced by the criteria C1 and C2. Hence, it is inferred that the criterion considered for the location suitability analysis for the construction of biomass-fired power plants holds significant in the states considered for the study. Although, the three states have abundant availability of rice husk, there are also a greater number of pre-existing SR. In such scenarios, it would be ideal and economical to increase the cogeneration capacity of the existing SR in the vicinity of biomass resources instead of constructing a new biomass-fired

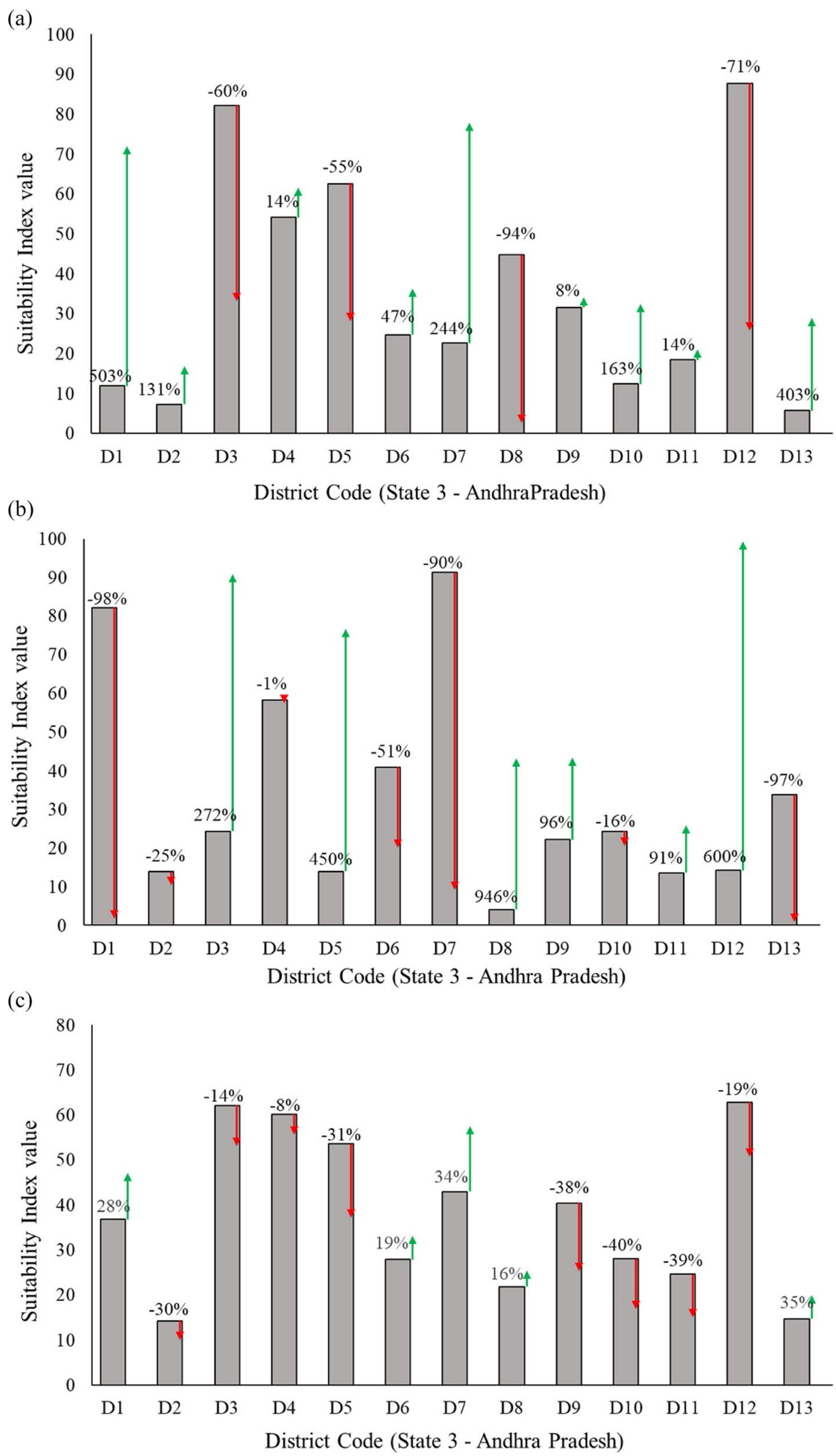

Fig. 11 Shift in suitability index for change in criterion weightage from 100% to -100%. (**a**) C1, (**b**) C2, and (**c**) C3

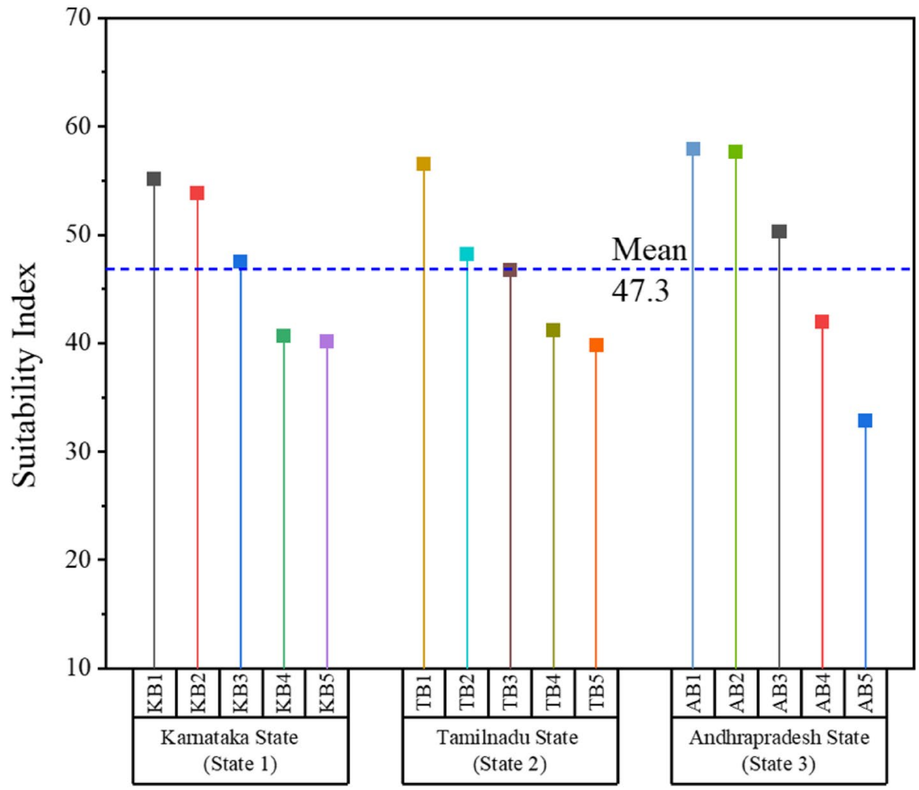

Fig. 12 Suitability index for the proposed locations in the three states

power plant. Hence, only five suitable locations in each state were proposed.

Hence, 15 out of 74 districts were found suitable for the construction of new biomass-fired power plants. The SI_n values of the potential locations for the establishment of biomass power plants are shown in Fig. 12. The mean suitability for the southern part of India is found to 47.3. A total of 9 out of 15 proposed suitable locations were above the mean suitability value, which infers that the southern part of India is rich in biomass potential contributing to the growth of sustainable energy.

4.4 Synergistic utilization of proposed plants with pre-existing cogeneration facilities

A study was carried out to assess the allocation of biomass among the proposed biomass-fired power plants and the pre-existing cogeneration plants, which encompass cogeneration facilities at 118 SR and 21 CT, in all 74 districts of the study areas. Efficient use of biomass is crucial for the cost-effectiveness of producing cleaner energy. Therefore, the allocation of biomass is crucial in the efficient production of power. Furthermore, it facilitates the efficient utilization of locally abundant biomass resources (in addition to rice husk) at the nearest cogeneration facility. Hence, the enhancement of the rural economy and the creation of power from biomass, which aids in meeting the energy demands of rural regions and completing the criteria for cleaner energy production by 2030 [2]. The proximity to the nearest cogeneration facility, whether it be a pre-existing facilities like SR or CT, or newly proposed biomass cogeneration plants, was calculated by performing an origin–destination analysis. This analysis was conducted using ArcGIS tool as an interface. All the study areas: Karnataka state, Tamil Nadu state, and Andhra Pradesh state, were analysed. All the districts were considered as the origin points (O). The proposed new biomass-fired power plants KB, TB, and AB along with synergistically utilised SR/CT were all included as destination points (D).

A total of 74 origins and 154 destination points were incorporated into the ArcGIS. The distribution of origin and destination points as per the study areas are SA-1: 30O, 62D (51S + 6CT + 5 KB); SA-2: 31O, 51D (39S + 7CT + 5 TB); SA-3: 13O, 41D (28S + 8CT + 5AB). Using network analysis in ArcGIS, the distances to all plant locations were calculated by considering the road network map of the study areas. The nearest plants were selected based on distance measurements to distribute biomass (rice husk) for generating power in an efficient

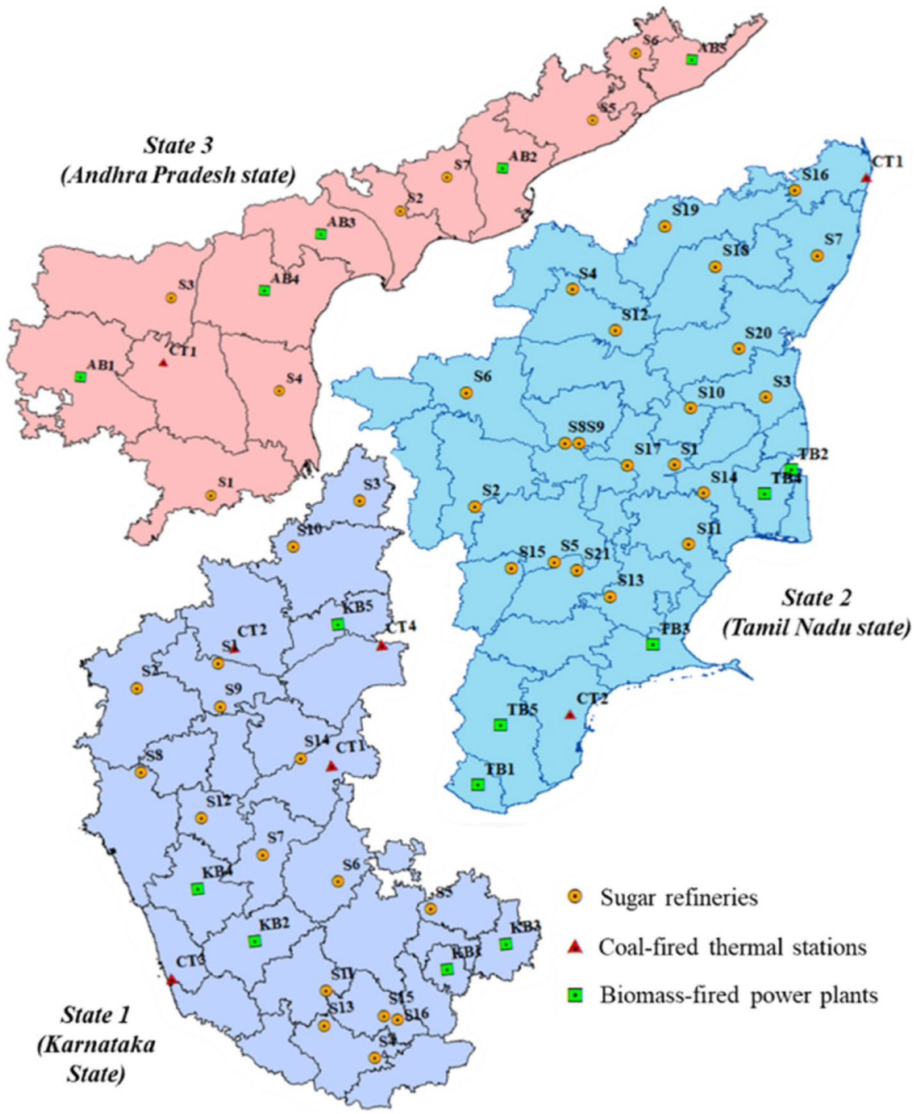

Fig. 13 Representation of potential sites for sustainable and cleaner power generation

and ecologically beneficial way. The synergistic distribution to the pre-existing SR and CT along with the proposed new biomass-fired plants were depicted pictorially in Fig. 13. Tables 2 and 3 show the list of all the suitable districts to which rice husk can be distributed for its effective utilization. The location of the pre-existing plants that can be synergistically utilized for cogeneration were represented in the form of latitudes and longitudes in the Table 3.

4.5 Environmental impacts of cleaner energy production

Although rice husk-based biomass energy presents evident environmental advantages, including the reduction of carbon dioxide emissions, it is essential to consider its broader environmental and social benefits. The production of biomass energy frequently necessitates considerable water consumption for the cooling process required. In areas with already strained water resources, this may intensify scarcity. Hence, utilizing water-efficient technologies and embracing sustainable management techniques can mitigate this impact. While the combustion of rice husk results in lower greenhouse gas emissions than fossil fuels, it is important to note that it can still generate air pollutants, including particulate matter, nitrogen oxides, and trace gases. Improper management of these emissions can lead to a decline in local air quality and present potential health hazards. Implementing cleaner combustion systems alongside advanced emission

Table 2 Synergistic distribution of proposed biomass plants for the three states considered for the study

Distribution of rice husk to the proposed new biomass-fired power plants		
District code	**Proposed ideal plant**	**District in which the plant is located**
Karnataka state		
D2 & D3	KB1	Bangalore Urban
D10	KB2	Chikmagalur
D20	KB3	Kolar
D26	KB4	Shimoga
D30	KB5	Yadgir
Tamil Nadu state		
D9	TB1	Kanniyakumari
D13	TB2	Nagapattinam
D17	TB3	Ramanthapuram
D23	TB4	Thiruvarur
D26	TB5	Tirunelveli
Andhra Pradesh state		
D1	AB1	Anantapur
D3	AB2	East Godavari
D4	AB3	Guntur
D7	AB4	Prakasam
D9	AB5	Srikakulam

control technologies has the potential to address this issue effectively.

Small-scale power plants may go with uncontrolled combustion, which is harmful due to the increased pollutants. Furthermore, rural small-scale power plants may utilize locally available waste, such as plastic along rice husk, which results in significant air pollution and hazardous gas emissions. The environmental impact of biomass energy includes not only combustion but also emissions generated during the collection, processing, and transportation of feedstock. Conducting a lifecycle assessment will help identify net emissions at each stage of production, ensuring that the overall benefits outweigh any potential drawbacks. After burning biomass to produce electricity, a significant quantity of bottom ash is generated. Usually, these residual ashes are often disposed of in landfills in rural regions. The disposal of bottom ash causes severe air pollution as well as land pollution. Besides, the cultivable land is filled with biomass bottom ash, which affects its fertile nature and has a negative influence on agriculture. Disposal of bottom ash from biomass plants to the rural region in large quantities for a prolonged duration causes severe leaching of hazardous elements into the soil. This concern can be addressed by reusing rice husk ash as a supplementary cementitious material in the construction sector instead of being disposed of as waste.

A quantitative analysis was done to compute the environmental impact of biomass (rice husk) in all three study areas considered. Only the rice husk-derived energy input was taken into account to calculate the amount of sustainable biomass-based power produced. The electricity generated within the realm of biomass sourced from rice husk, is only 23% of the total input energy. The calorific value of rice husk is 15,608 kJ kg^{-1} [34, 35]. The energy generation capacity for study regions 1, 2, and 3 is estimated to be around 390, 719, and 904 MW, respectively, with an assumed efficiency rate of 23% [34]. Thus, the regions considered in the study collectively contributes to approximately 466 MW of cleaner energy in terms of power can be produced in a sustainable way. This is a highly thoughtful value that has a significant impact on the environment. Indian thermal plants mostly utilize bituminous coal, that falls under the sub-critical category and exhibits around 34% efficiency. To produce 466 MW of power, roughly 247 t of coal with a calorific value of 20,000 kJ kg^{-1} is required. Bituminous coal, containing 70% carbon, produces 2.57 kg of carbon dioxide kg^{-1} coal burnt. Therefore, the production of 466 MW of electricity leads to the release of approximately 634 t of CO_2, a substantial amount. Utilizing rice husk for cleaner energy production results in low CO_2 emissions. The CO_2 corresponding emissions per MWh resulting from rice husk-based cogeneration is about 17 [34]. It is important to note that only 1.3% of carbon emissions were observed when compared with coal to generate 466 MW of power. This significant reduction in carbon emissions that will have a huge impact on the environment is the primary benefit of the current study.

Coals are classified based on their total sulphur content: low-sulphur (<1%), medium-sulphur (<3%), and high-sulphur (≥3%) [36]. Numerous investigations have indicated that thermal power plants in India predominantly use coal characterized by low sulphur content. The typical sulphur content in coal utilized for power generation is around 0.5% [37–39]. Generating 1 MWh of power from bituminous coal results in an observed emission of 12 kg of sulphur dioxide (SO_2) [40]. Similarly, the utilization of rice husk as a fuel resulted in approximately 0.035 kg of SO_2 emissions for every 1 GJ of energy produced [41]. To generate an equivalent power output of 466 MW, the SO_2 emissions from utilizing rice husk account for merely 1.1% of the total emissions produced by coal. The reduction in SO_2 emissions is attributed to the lower sulphur content found in rice husk when compared to coal [41, 42]. Consequently, a significant reduction of approximately 99% in SO_2 emissions can be achieved through the utilization of available rice husk for equivalent amount of power generation.

Table 3 Synergistic distribution of SRs /CT to all the districts for the three states considered for the study

Distribution of rice husk to the pre-existing sugar refineries for cogeneration

District code	Proposed ideal plant	Latitude N (DD*) (°)	Longitude E (DD*) (°)	Distance (km)
Karnataka state				
D1	SR1	16.3555	75.6662	15.40
D4	SR2	16.1930	74.8178	9.79
D6	SR3	17.8629	77.2883	1.83
D8	SR4	12.1052	76.7578	54.41
D9	SR5	13.5775	77.5089	47.69
D11 & D27	SR6	13.9672	76.6097	23.68 & 68.19
D13	SR7	14.3290	75.8806	4.62
D14 & D29	SR8	15.3153	74.7613	54.72 & 67.26
D15	SR9	15.9069	75.6401	74.04
D16	SR10	17.4624	76.5634	40.06
D17	SR11	12.8521	76.3535	41.89
D18	SR12	14.7756	75.3122	15.06
D19 & D23	SR13	12.4994	76.2928	82.03 & 55.57
D21	SR14	15.2814	76.3772	35.00
D22	SR15	12.5336	76.9033	12.81
D25	SR16	12.4819	77.0409	47.40
Tamil Nadu state				
D1	SR1	10.8992	78.8510	49.33
D4	SR2	11.4477	79.5489	24.41
D3 & D27	SR3	10.5617	77.3355	65.08 & 49.58
D5 & D11	SR4	12.3242	78.0736	27.74 & 18.24
D6 & D12	SR5	10.1105	77.9350	33.66 & 24.38
D7	SR6	11.4858	77.2697	14.14
D8	SR7	12.5975	79.9448	6.07
D10	SR8	11.0756	78.0220	29.87
D14	SR9	11.0768	78.1286	30.14
D15	SR10	11.3573	78.9745	13.80
D16	SR11	10.2528	78.9635	14.10
D18	SR12	11.9894	78.4014	41.70
D19	SR13	9.8324	78.3629	25.97
D20	SR14	10.6706	79.0753	24.17
D21	SR15	10.0614	77.6128	37.67
D22	SR16	13.1247	79.7715	34.57
D25	SR17	10.8968	78.4961	6.77
D28	SR18	12.5076	79.1682	13.96
D29	SR19	12.8339	78.7797	45.24
D30	SR20	11.8402	79.3406	12.96
D31	SR21	10.0477	78.1077	70.16
Andhra Pradesh state				
D2	SR1	13.2345	79.1110	25.57
D5	SR2	16.6210	80.9350	16.78
D6	SR3	15.4513	78.5135	62.41
D8	SR4	14.4733	79.7656	7.47
D10	SR5	17.8052	82.9617	38.98
D11	SR6	18.6060	83.3728	23.08
D12	SR7	17.0396	81.4180	14.07

Table 3 (continued)

Distribution of rice husk to the pre-existing coal-fired thermal stations				
District code	Proposed ideal plant	Latitude N (DD*) (°)	Longitude E (DD*) (°)	Distance (km)
Karnataka state				
D5	CT1	15.1817	76.6767	21.33
D7	CT2	16.4967	75.8425	67.02
D12 & D28	CT3	13.1608	74.8053	78.19 & 55.78
D24	CT4	16.3586	77.3353	56.97
Tamil Nadu state				
D2	CT1	13.2358	80.3058	23.79
D24	CT2	8.8844	78.0544	7.53
Andhra Pradesh state				
D13	CT1	14.7014	78.4581	54.85

* DD-Deciamal Degree

Coal stands as the predominant contributor to nitrogen oxide (NOx) emissions globally, attributed to its higher nitrogen content compared to other fossil fuels. Temperature, fuel properties, and the fuel–air ratio are critical elements that affect both the generation and disintegration of NOx emissions [43]. Nitric oxide generally constitutes 90–95% of the nitrogen oxides generated during the combustion of coal, while nitrogen dioxide accounts for the remaining 5–10% [44]. Research indicates that generating 1 MWh of power from bituminous coal results in 4.6 kg of nitrogen oxide emissions [40, 45]. In a similar vein, the utilization of rice husk as a fuel resulted in approximately 0.79 kg of NO emissions for every 1 MWh of power generated [41]. To generate an equivalent output of 466 MW of power, the utilization of rice husk leads to a reduction of approximately 83% in nitrogen oxide emissions, which is substantial. The higher ash content found in Indian coal leads to increased emissions of particulate matter [46]. The emission factor for particulate matter resulting from coal combustion in thermal power plants is considerable. Besides, research findings indicate that the emission factors for $PM_{2.5}$ resulting from coal combustion vary between 0.8 and 9.9 g kg^{-1}. The variations observed indicate that both the type of coal and the combustion conditions significantly influence the emission factors. For example, the emission factors for $PM_{2.5}$ resulting from the combustion of raw bituminous coal vary between 1.9 and 7.0 g kg^{-1} [47]. Kong et al. documented a value of 9.9 g kg^{-1}, whereas Zhang et al. indicated 2.4 g kg^{-1} [48, 49]. When burning rice husk for energy generation, $PM_{2.5}$ values have been reported to range from 1.4 to 2.7 g kg^{-1} of rice husk [50]. This clearly indicates the decrease in $PM_{2.5}$ emissions resulting from the transition from conventional coal to rice husk.

In addition, the construction of new power plants that use rice husk as the main energy source offers advantages such as the production of cleaner energy, low and affordable costs for transportation of biomass to the closest cogeneration facility, and enduring sustainability. Furthermore, the proposed new biomass plants can also utilize other agricultural wastes available in the local vicinity with suitable calorific value to generate sustainable and cleaner energy in the form of power. Residues from agricultural waste like rice husk ash and sugarcane bagasse ash are generated as secondary products from various plants, such as SR, CT, and newly proposed and constructed biomass-powered plants. Ashes from various biomasses can be assessed for their pozzolanic properties to check their use as supplementary cementitious material. The biomass ashes collected have great potential for use in the construction industry as an eco-friendly substitute for cement. Thus, expanding the availability and accessibility of these supplementary cementitious materials can further aid in decreasing emissions. Hence, the idea of creating new biomass-fired power plants by integrating the pre-existing SR and CT that use biomass as fuel significantly impacts sustainability and the environment. This initiative thereby contributes to fulfilling the goals of cleaner energy production and circular economy.

This study also emphasizes the importance of cost-effectiveness in assessing the feasibility of rice husk utilization for energy production. The large study areas considered for synergistic utilization are further divided into small zones called districts. For example, a state is divided into more than twenty districts. Consequently, the maximum procurement distance is restricted within these small zones of districts. For example, Villupuram, the largest district in Tamil Nadu, is situated within a distance radius of approximately 35 km after zoning. This is because of optimal and economic logistic perspective. It leads to responsible consumption of locally available biomass resources like rice husk with minimum transportation costs. The accessibility of rice husks for cogeneration in the current plants is assessed by considering distance as one of the key criteria. The criterion for the aforementioned metric is C2: the proximity of biomass to the nearest cogeneration facilities, sugar mills or thermal plants. Biomass distribution for synergistic use is determined by the availability of neighbouring resources at the district level across all study locations. This resembles the procurement of sugarcane grown in adjacent villages by sugar mills. Consequently, the procurement and transportation expenses closely resemble the existing logistics of sugar mills that source sugar cane. Therefore, the cost–benefit analysis of rice husk, encompassing material acquisition and transportation, is comparable to that of sugar cane.

In the case of coal-fired thermal plants, coal is either sourced from Indian coal mines or imported from other countries. The principal coal mines in India that fulfill a significant portion of energy requirements are situated in Jharkhand, Odisha, Chhattisgarh, West Bengal, Madhya Pradesh, Telangana, and Maharashtra. Nevertheless, in the study regions, there is a lack of substantial coal mine availability. The state of Karnataka lacks coal resources and relies on coal imports from other states to meet its thermal requirements. Although Andhra Pradesh possesses a portion of the Singareni coal mines, the principal operations are conducted in the neighbouring state of Telangana. The Cuddalore district in Tamil Nadu utilizes Neyveli lignite mines that fulfill the energy requirements of the industrial sector. Lignite, however, is distinct from the hard coal (bituminous) commonly extracted and utilized in the majority of thermal power plants in India. Consequently, leveraging the rice husk readily available in nearby district regions is significantly more advantageous from a logistical aspect. A detailed view of the implementation and operational procedures of this biomass plant, currently in operation, will improve comprehension of the economic feasibility of using rice husks as a renewable energy resource. Thus, a case study associated with cost-effectiveness by switching over rice husk-based energy production is also presented in the subsequent paragraph.

4.5.1 Case study: Husk Power Systems (HPS) in India

HPS serves as a significant case study in the efficient collection and utilization of rice husk in India [51]. HPS produces energy from rice husks, delivering electricity to rural communities. HPS sources rice husks directly from nearby rice mills. In certain cases, company-owned tractors are utilized to collect the husks, thereby guaranteeing a consistent supply for their power plants. The organization keeps a stockpile of rice husks to ensure uninterrupted functioning, particularly during monsoons. The collected biomass is utilized as fuel for electricity generation. The leftover biochar from the process is utilized in the production of incense sticks, rubber, and manure, showcasing an integrated strategy for waste management. In HPS, there are about 150 mini-grid plants. Each plant with gasifier-based power plants generally generates between 25 and 100 kW of electricity, which is adequate to supply the energy requirements of approximately 400 to 500 households. A 100-kW plant generally caters to 400–500 households, generating an annual revenue of about $1.9 million for one mini-grid plant. Thus, a total of HPS with 150 mini-grid plants generates annual revenue of about $290 million. The gasification process yields biochar, which is a valuable by-product. About 1.5 t of biochar (value-added by-product) is produced for every ton of rice husks utilized. Furthermore, HPS projects are also eligible for carbon credits because of their emphasis on renewable energy. Additionally, supplementary income of about 17.8% of total revenue is generated from biochar and carbon credits. Thus, HPS serves as an illustration of the economic advantages associated with rice husk-based biomass plants. The proposed biomass facilities can adopt comparable strategies and approaches to ensure both economic and environmental sustainability.

The model presented in this study provides a robust and flexible framework that could serve as a blueprint for assessing various forms of agricultural waste, such as sugarcane bagasse, wheat straw, rice straw, etc. These materials are widely prevalent in various agricultural regions and have unique energy potentials and chemical compositions that might be efficiently integrated into the proposed methodology. With marginal modification of input parameters with respect to the calorific value of any type of biomass, the proposed framework can be adopted. Moreover, the present method can provide valuable insights for sustainable solutions. Implementing this methodology on these potential materials may uncover novel prospects for minimizing agricultural waste and improving renewable energy portfolios. Furthermore, regions with distinct agricultural products will benefit from the customized approaches that correspond with their agricultural waste availability and energy requirements. The proposed methodology also aligns in pursuit of UN SDG's, contributing to clean and affordable energy (SDG-7) and promoting sustainable consumption and production (SDG-12).

5 Conclusions

The current study examined the feasibility of rice husk-based cleaner energy production. Moreover, the potential for synergistic utilization of proposed new biomass-fired plants and pre-existing sugar refineries/coal-fired thermal stations are also investigated. Location suitability was evaluated using suitability index values, and the reliability of the results was confirmed by sensitivity analysis. This study also assessed the cleaner and sustainable way of electricity production and its impact on the environment using rice husk as a potential substitute for coal. Specific conclusions derived from the study are given below.

- Location suitability analysis is conducted, and it is observed that the district's suitability index assessment is greatly affected by the criterion of rice husk availability (C1) and proximity to pre-existing sugar refineries/coal-fired thermal stations (C2). The sensitivity analysis also shows that criteria C3 has less influence when compared to criteria C1 and C2.
- 15 locations are identified as suitable for the establishment of new biomass-fired power plants in the selected study areas. In the remaining regions, the synergistic use of existing plants is found to be beneficial instead of new plant.
- Highest suitability index values of 56.5, 55.1, and 50.3 are found for the districts D23, D30, and D7 for the study areas Tamil Nadu state, Karnataka state, and Andhra Pradesh state, respectively, which signifies the locations to be extremely ideal for the construction of new rice husk-based power plants.
- The mean suitability value is 47.3, which indicates that southern regions of India are rich in biomass potential, contributing to the production of cleaner energy.
- The adoption of synergistic utilization of SR/CT plants has led to a significant decrease in travel time and distance and carbon dioxide emissions. For example, a new biomass-fired power plant in district D7 of Andhra Pradesh state has reduced the transportation of biomass to the pre-existing cogeneration facilities by around 135 km for a single trip. Similarly, a notable reduction in distance of about 131 and 121 km was observed in the districts of D9 and D26 of Tamil Nadu and Karnataka states respectively, for a single trip.
- The power produced from utilizing rice husk in southern regions of India amounts to approximately 466 MW, a substantial contribution. It produces only 8 t of CO_2 emissions unlike the conventional method which gives 634 t of carbon emissions for the equivalent quantity of power generated.
- Use of rice husk as an alternative to coal results in reduction of carbon dioxide emissions by approximately 98.7%. Similarly, a notable reduction of 99% and 83% in sulphur dioxide and nitrogen oxide emissions are noted. Therefore, using biomass significantly reduces carbon emissions by producing cleaner energy in a more ecologically sustainable and enduring manner.

In addition to rice husk, many other agro-wastes available in the local vicinity, which have potential to be used as biomass can also be cogenerated. Furthermore, the proposed plants, along with sugar refineries/coal-fired thermal stations, generate ashes as secondary by-products. These ashes have a high likelihood of being utilized as additional cementitious materials in the construction sector. Therefore, using agricultural waste to produce cleaner electricity results in the production of agro-waste ashes as secondary by-products. These ashes have the potential to be employed as pozzolans and can act as supplemental cementitious materials in the building industry. Therefore, the present study makes a valuable contribution to achieving a circular economy by effectively integrating the agricultural, energy, and construction sectors.

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Authors' contributions
Jyothsna G: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing original draft. A. Bahurudeen: Validation, writing review & editing, Supervision. Prasanta. K. Sahu: Writing review & editing, Supervision.

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Data availability
All data used in the study will be made available on request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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