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Assessment of the solar energy–agriculture–water nexus in the expanding solar energy industry of India: An initiative for sustainable resource management

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ABSTRACT

The rapid expansion of solar energy in India poses challenges in the context of cropland encroachment and water-resource scarcity. To help address these challenges, we used open access satellite observations and GIS technologies over Earth Engine platform to devise the Solar Panel Index (SPI) for efficient detection of solar farms, achieving a Land use/Land cover classification accuracy of 89 %. We have used cropland, water availability, power grid and land surface temperature data-sets for generation of land suitability map. Sentinel-2 data-sets along with SPI were used to develop solar farm locations and their estimated installed capacity within the study area. The outcomes from the study depicted that over 40 % of all solar farms in the country are located on agricultural land, with the highest seen in Karnataka (73.55 %) followed by Tamil Nadu (68.81 %). Furthermore, high installed capacity coincides with low groundwater depths, exacerbating local water strain. Madhya Pradesh was found to have almost no power plant located within 5 km of surface water bodies. Our findings emphasize the significance of the solar-agriculture-water (SAW) nexus for sustainable development. Using high-resolution Land Suitability Map (LSM) as a decision-making criteria for allocating land for power generation reveals that Rajasthan holds the highest potential for solar energy installation. Our integrated approach considering the interplay between solar-energy production, agriculture, and water-resource management contributes to the sustainable growth of the solar-energy sector and regional development.

1. Introduction

Rising greenhouse gas (GHG) emissions, which put our planet's climate and ecosystems in serious problem, are an urgent global issue [1]. To tackle this problem, societies worldwide are increasingly adopting low-carbon renewable energy sources, particularly solar power. In the past decade, there has been a remarkable global surge in the installation of Photovoltaic (PV) solar panels, driven by various government schemes and incentives that have encouraged both individuals and large-scale enterprises to invest in solar power generation. This trend has led to the establishment of solar farms encroaching upon agricultural croplands in regions such as the USA [2], Canada [3], and Europe [4]. Despite the growth in solar energy, the challenge of balancing renewable energy expansion with

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agricultural needs remains a key concern, underscoring the importance of strategic land-use planning and sustainable coexistence. The United Nations and its member states adopted Sustainable Development Goals (SDG) in 2015 (www.unfoundation.org), marking a critical turning point for countries to promote renewable energy production. This led to switching the focus from coal-based generation to PV Solar Energy [5]. India is the third largest producer and consumer of electricity in the world [6]. However, only 10 % of its electricity consumption is covered by PV solar power, and only 25 % of its consumption is covered by all renewable sources combined (www.renewablesindia.in/).

The National Solar Mission launched in 2010 is a strong component of the national action plan for climate change [7]. In the last decade, solar panel installation in the country has been rising drastically from merely 141 in 2010 to 40,085 in 2021 (Fig. 1). As of 2021, the installed capacity of the country is around 40 GW s [6]. This is a small portion of what the country has set the target for, that is of 280 GW by the year 2030 [8]. Previously, India has fulfilled its set target four years prior the schedule [9]. Over the coming years, it is expected that the overall installation expenses will decrease as a result of declining PV prices, and the land footprint required for utility-scale PV systems is also projected to shrink due to rapid technological advancements [10]. Some ambitious initiatives like 'One Sun, One World, One Grid' bring more possibilities in exceeding the goal [11]. The idea of the project is to connect 140 countries around the world with a common grid, especially the countries lying on the equatorial belt, to get the maximum out of solar energy. India already exports electricity to its neighboring countries like Bangladesh, Nepal, and Bhutan [12]. This project may further boost motivation to invest into solar energy as it can boost further economic growth.

Large-scale renewable solar power projects face various challenges, including technical obstacles like the need for advanced monitoring, resource variability, location compatibility, and maintenance issues [13]. The energy production of such large systems can be sustained for 20–30 years, making them a viable long-term solution [14]. Solar parks have shown the potential to contribute significantly to fulfilling energy demand in Jordan [15]. Whereas, the rooftop PV systems have shown considerable power potential in Sweden, with more than 10,000 MW h annually [16]. The total electricity generation potential of rooftop PV projects was estimated to meet 76.1 % of the social electricity consumption in Nanning City, indicating that rooftop PV systems have the potential to fulfill a significant portion of the energy demand [17]. While the PV system contributes to renewable transition and reduces dependence on external grids, it cannot fully fulfill the electricity demands in the district due to a gap between production and loads [16].

One major requirement to fulfill this objective of solar projects is the availability of land. A study by NREL, states that the total land use requirement for solar power plant projects is about 8.9 acres/MW [18]. If we have to estimate the total land requirement of 280 GW solar power with this input then, it estimates to more than 1 million ha area. It is approximately double of 10 major cities of India combined in area. Agricultural croplands show great potential for PV power potential, as it provides land convenient for power generation from geolocation point of view [19–23].

India, an agrarian country, has second largest farm output in the world [24] and as of 2018, the agricultural sector employed more than 50 % of the Indian workforce, contributing about 17–18 % of the country's GDP.

India is the world largest producer of pulses and spices, and the second largest producer of rice, wheat, sugarcane, groundnut, vegetables, fruits and cotton [25] and even with such a huge food production, food security is a concern in the country. According to UN India (*in.one.un.org*), around 195 million people in India are undernourished, making it a quarter of the world's hunger burden. Rising solar power will bring more burden onto the food production stemming from agricultural land encroachment. The water resources in any region are generally used for agriculture, industrial and domestic purposes. Only 18 % of the rainwater is used effectively while 48 % enters the river and most of which reaches the ocean [26] whereas rest is lost via evaporation, transpiration and runoffs. Water is also used for cleaning solar panels and approximately 2 L of water are used to clean one solar module [27]. The industrial field visit to Bhalda solar farm in 2020 substantiates the point. This water is transported from a long distance in tanker trucks regularly. For a medium size solar plant of about 10 MW, monthly estimated water requirement is 165,000 L [28]. Rising solar power will also demand for more water, further making more water stress in the region.

The main motive behind solar energy is to bring sustainable, affordable and clean energy (SDG#7). Unexpectedly it is having a severe consequence on eradication of zero hunger (SGD#2) and providing clean water and sanitation (SDG#6). 'Solar Energy-Agriculture-Water' (SAW) nexus is at the core of the sustainable development of modern society. The nexus should be considered over individual sectors in development strategies of the countries [29]. The SAW nexus (Fig. 2) refers to the interconnected relationship between these three sectors, and how they can work together to address challenges related to sustainability, food security, and climate change. Solar energy can be harnessed in agriculture in many ways, such as using solar panels to power irrigation systems or to generate electricity for farm operations [30] and this can reduce the reliance on fossil fuels, increase energy efficiency, and reduce

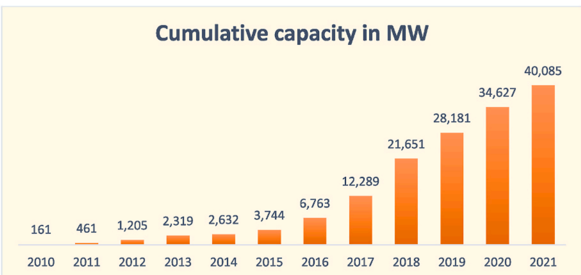


Fig. 1. Cumulative installed capacity of solar energy.

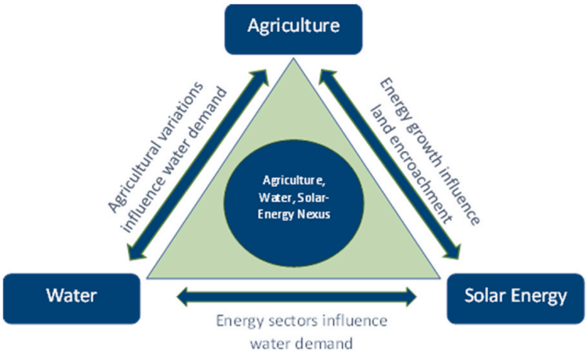


Fig. 2. Dynamic relationship between Solar-Agri-Water nexus.

greenhouse gas emissions. Water is a crucial resource in agriculture, and solar energy can help to address water scarcity by powering desalination plants, pumping groundwater, or providing energy for irrigation systems [31]. In arid nations, particularly those located in desert regions, solar PV water pumping systems have the potential to mitigate the impacts of water scarcity, enhance crop yields, and alleviate the challenges posed by droughts during dry seasons [10]. Additionally, solar energy can be used to power sensors and other technologies that can help farmers manage their water resources more effectively [32].

In turn, agriculture can play a role in supporting the expansion of solar energy by providing land for solar farms or by integrating solar panels into their operations [33]. This can provide additional income streams for farmers, increase the resilience of the energy grid, and support the transition to renewable energy. Overall, the SAW nexus represents an opportunity to create more sustainable and resilient food and energy systems that benefit both people and the planet. On the negative side, if agricultural land is completely converted into solar farms, it could lead to a reduction in the area available for crop cultivation, thereby threatening food security [34]. This is particularly concerning in regions where arable land is already scarce. Inadequate infrastructure management, land utilization, the generation of waste, and the depletion of natural resources are all instances of environmental stressors that impact the nexus framework [35]. Moreover, solar panels can impact local water cycles. They might reduce groundwater recharge by limiting the amount of rainwater that seeps into the ground, and also affect local microclimates, potentially altering the suitability of the area for certain crops. Another concern is that the increased demand for water to clean solar panels could exacerbate water shortages in areas already experiencing water stress. This is particularly important in arid regions that are attractive for solar power due to their high solar irradiation [36]. While solar power is a critical part of our renewable energy future, careful planning and management are needed to ensure that its expansion does not negatively affect agricultural practices and local ecosystems.

Globally, agriculture is the largest consumer of water, accounting for 70 % of total water usage on a global scale [37]. Irrigated agriculture, which covers roughly 20 % of cultivated land, contributes a substantial 40 % to the overall global food production [38]. Notably, irrigated agriculture boasts a productivity rate at least double that of rainfed agriculture on a per-unit-of-land basis, enabling increased production intensity and crop diversity [39]. However, the intensive extraction of groundwater for irrigation purposes leads to the depletion of water resources. Initiating shifts in water allocation between sectors and directing water away from agriculture will require simultaneous enhancements in water use efficiency and the refinement of water delivery systems. Improving water management within agriculture is often hampered by insufficient management strategies, which are crucial for enhancing the good use of agricultural water, thus ensuring optimal production and yields [40].

Previous studies have shown, how the existence of dominant energy industries change the dynamics of the Energy-Population-Urbanization nexus in the society [41,42] Numerous studies have employed the 'Life Cycle Assessment' (LCA) approach, a quantitative tool designed to evaluate the environmental advantages of energy alternatives [43]. Additionally, other investigations have used the Analytical Hierarchy Process (AHP) method to assess renewable energy resources via a multicriteria analysis [44]. Remote sensing and Geographical Information System (GIS) technologies are vital tools in providing potential sites for installation of solar power plants [45]. It can provide a comprehensive understanding of the interdependencies between water, energy, and food systems, and can help to identify solutions that promote sustainability and resilience.

The Solar Panel Index (SPI) is a novel algorithm introduced in this study that utilizes data from multispectral satellites to improve the identification of PV solar farms. It has been important in locating power plants nationwide, and enhancing the accuracy of Land Use and Land Cover (LULC) map generation. Previous studies have also demonstrated the application of computer vision algorithms on high-resolution imagery and aerial photography [46]. Some research has underscored the significance of texture in the mapping of solar power plants [47]. Numerous studies leverage Convolutional Neural Networks (CNNs) for detecting solar panels, incorporating advanced models like Faster-RCNN, a ResNet-50 classifier [48], while others employ the EfficientNet-B7 classifier [49] or the YOLO v5 algorithm [50]. The primary sources of images are aerial datasets and satellite images, obtained through the Google Map Static API [48,49]. Some images exhibit lower resolution due to the incorporation of thermal bands [51]. Various limitations exist, such as hardware restrictions limiting the mini-batch size for online training to a single image, potentially impacting the learning trajectory and the overall efficacy of the method [48]. If lens distortions in thermal images are not corrected, it could negatively impact the accuracy of solar panel detection [51]. Additional challenges arise due to memory constraints and the associated costs of GPU instances [49]. In certain instances, the dependency on local descriptors is significant, and inaccuracies therein can result in substantial detection errors [50].

This study introduces a detection algorithm applicable to openly available optical satellite data, which can be utilized for solar capacity generation estimation. The integration of this detection index algorithm with satellite data enables real-time monitoring of solar power expansion in a straightforward manner. This research underscores the utilization of SPI in pinpointing power plant locations and conducting environmental impact analyses on a national scale. The Google Earth Engine platform has significantly streamlined workflow processing. Previous studies have evaluated potential solar power generation in India [52], leveraging the proficiency of remote sensing and GIS technologies [53]. This study continues to harness these powerful tools in the monitoring of solar power.

Remote sensing can also support evidence-based decision-making in resource management, which is crucial for addressing the complex challenges of the water-energy-food nexus [54]. This research employs optical satellite data from the Sentinel-2 mission and Landsat to study the growth of solar power generation and its interaction with various environmental factors. Additionally, various Geographic Information System (GIS) datasets were utilized for assessment and map generation purposes. Our analysis focused on a ten-year period, observing changes in Land Use and Land Cover (LULC) within the Pavagadh solar park in India. This investigation shed light on alterations in irrigation practices and the management of water resources within the region. This study further corroborates the strong correlation within the components of the SAW nexus through the use of remote sensing. Previous research has focused on creating land suitability maps for solar power installation in various regions such as Egypt [55], Iran [56], Korea [57], Mongolia [58], and Saudi Arabia [59]. We adopted a similar approach but on a larger scale, integrating the sustainability of food via agricultural practices, water resource utilization, and renewable solar power generation.

This research proposes a land suitability map for the optimal use of space for renewable solar energy development. We have analyzed India's existing renewable solar energy policies and the issues related to farmland-based solar power systems. Based on this analysis, we offer suggestive guidelines for promoting the solar power industry sustainably while mitigating environmental impacts. A

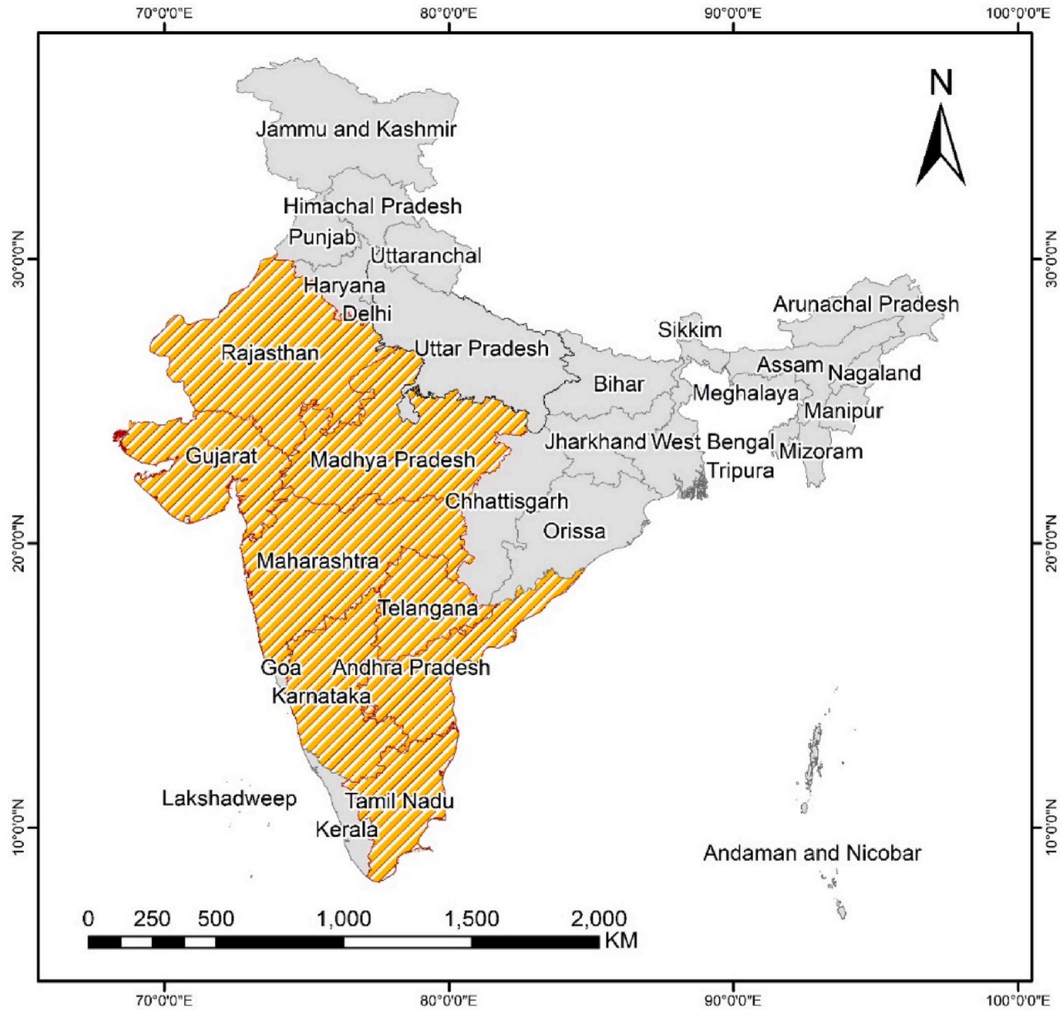


Fig. 3. The geographic location of the study area map showing the top eight states with highest installed capacity of photovoltaic solar power.

case study of the Pavagadh solar power plant in Karnataka was conducted to comprehend the drivers of the SAW nexus. This study highlights the role of geospatial remote sensing in monitoring the components of the nexus. The ultimate outcome of this study, a Land Suitability Map (LSM), is intended to furnish decision-makers with a comprehensive tool to facilitate land allocation planning for the development of solar power projects. The objective of the study was to develop a SPI for creating datasets of solar farm locations and their estimated installed capacity and to create a LSM for upcoming solar farm installation keeping in view of nexus from the current scenario. The novelty of the study includes the depiction of the relationship between the solar-agriculture-water (SAW) nexus along with suggestive policies for sustainable management of resources. By considering these objectives, policymakers and stakeholders can make informed decisions to promote the coexistence of solar energy production, agriculture, and water resource management.

2. Study area

India is situated in the southern part of the Asian continent, between latitudes 8° 4' and 37° 6' north of the Equator, and longitudes 68° 7' and 97° 25' east. The country experiences an average annual rainfall of approximately 1250 mm, but this precipitation is highly variable [60]. Some regions witness abundant rainfall, while others receive very little. The Thar Desert and the Himalayan Mountain range play pivotal roles in shaping the country's climate. Fluctuations in temperature and pressure over the Indian Ocean, the Arabian Sea, and the Bay of Bengal significantly influence the distribution and quantity of rainfall across India. The recorded highest and lowest annual rainfall in India differs by approximately 1178 cm, emphasizing the extent of this variability [60]. India's rainfall shows irregular patterns throughout the year, with a distinct monsoon season prevailing over most of the country from June to September. India ranks 133 out of 180 nations around the world for its water availability [61]. Water plays an important role in the effective working of solar power plants. Apart from that, temperature is also an important factor in efficient power generation. As temperature rises the efficiency of solar panels drops significantly. In arid regions like That desert of Rajasthan, temperature goes as high as 47 deg Celsius [36]. The average temperature across the country is 27 deg Celsius (worlddata.info/asia/india/climate.php). As of June 2023, India has achieved a solar power installed capacity of approximately 70 GW and has established 42 solar parks to facilitate solar plant development [62]. Top eight states with highest installed capacity (see Fig. 3) are Karnataka, Rajasthan, Andra Pradesh, Madhya Pradesh, Maharashtra, Telangana, Tamil Nadu, and Gujarat (mnre.gov.in/solar/current-status/). These states contribute about 86.87 % of the total installed capacity of the country with Karnataka and Rajasthan comprising 18.77 % and 13.98 % of total power production respectively.

3. Methodology

The overall methodology used in this study was to (1) identify the distribution of solar panels in India using a newly developed 'Solar Panel Index', and (2) to quantify change in land use caused by establishment of solar farms on agricultural land. Further quantification was done for water resources availability in solar farms of different states, by using secondary ground & surface water datasets and the solar panel distribution maps derived from this study. In addition, the LSM map was generated using a multi-criteria decision-making model as a guiding material for land allocation of solar power generation. The correlation analysis was carried out between SAW (i.e., solar-agri-water) classes to evaluate the nexus at regional scale. The evaluation was focused on one particular solar power plant: Pavagadh solar power park, located in Tumkur district in Karnataka due higher installed capacity and its proximity to agricultural land [63]. The Pavagada Solar Park in Karnataka, India, is an example of large-scale renewable energy projects being built on underutilized land to meet India's target of 450 GW of renewable energy by 2030.

Sentinel-2 and Landsat 8 optical satellite data-sets from the year 2020 were used to monitor solar farms. The data was accessed from Google Earth Engine platform (GEE) and directly used for processing. GEE data catalog consists of atmospherically corrected Surface Reflectance images. Cloud mask and arithmetic computation of image collection can be easily done on the platform. Additionally field visit was done for validation point regarding the impact of solar farm installation on land in Avaada Solar power plant, Chalisgaon, Maharastra.

3.1. Solar Panel Index (SPI)

The methodology of this study hinges on the novel Solar Panel Index (SPI), an arithmetic equation that employs six multispectral bands from widely available optical satellite data. These include the Blue, Green, and Red bands, as well as the Near-Infrared, Shortwave Infrared Band 1, and Shortwave Infrared Band 2. Solar farms are typically installed on flat terrain with panels primarily directed towards the south (in the Northern Hemisphere). The size of these farms is determined by their capacity to produce energy at a given time, which is usually measured in watts. Solar power plants' area with a capacity exceeding 1 MW, are termed as solar farms, which are focus of this study (www.solarlandlease.com/size-of-a-solar-farm). They usually cover an area up-to 4 ha–8 ha [64]. It's important to note that these farms are surrounded by various types of land, including grasslands, shrublands, croplands, and arid land, all of which may influence the surface reflectance detected by satellite sensors. The structures of these solar power plants are visible from space, making them ideal for satellite monitoring. Open-source satellite data from the Sentinel-2 and Landsat series, have been frequently used in various studies for monitoring purposes [65], and can be used to track solar expansions too. The SPI algorithm incorporates three bands from the visible spectrum (Red, Green, and Blue) and three bands from the near-infrared section (Near-Infrared, Shortwave Infrared Band 1, and Shortwave Infrared Band 2). This configuration enables the SPI to cancel out background reflectance intensity, thus highlighting the solar panel area and reducing false-positive responses. To ensure diverse environmental conditions, sample points were drawn from various solar farms across the country. We first recorded and examined the spectral reflectance profiles of PV solar panels. The images used for this study were retrieved and analyzed from the GEE. These were pre-processed and atmospherically corrected to ensure clarity in the results.

The surface reflectance plots were thoroughly studied to understand the reflectance pattern of PV solar modules. Subsequently, we formulated the equation as follows:

$$SPI = 0.3\text{x}(2\text{Blue} - \text{Red} - \text{Green})/(2\text{Blue} + \text{Red} + \text{Green}) + (2\text{SWIR1} - \text{SWIR2} - (0.7\text{xNIR}))/(2\text{SWIR1} + \text{SWIR2} + (0.7\text{xNIR})) \quad (1)$$

Raster images corresponding to these plots are presented in the results section. Finally, we also discussed the role of SPI in the improvement of classification accuracy via machine learning, a topic that will be discussed in more detail in the table included in a later section.

3.2. AHP model

Analytical Hierarchy Process model involves pairwise comparison of various criteria. A matrix of pairwise comparison of each criterion is built based on input values from experts. The value scale ranges from 1 to 9. The matrix is formed by using Saaty's method.

$$\text{Aw} = \begin{vmatrix} 1 & p & q \\ 1/p & 1 & r \\ 1/q & 1/r & 1 \end{vmatrix} \quad (2)$$

Later the matrix is normalized by dividing it by its relative weights. A further consistency check is done following Saaty's formula:

$$CI = (\lambda \max - n)/(n-1) \quad (3)$$

Here, n is the size of the matrix that is 5, whereas λ max is the product of Aw and Nw, which is equal to 5.139.

Consistency Ratio (CR) is estimated using following formula:

$$CR = \text{CI}/\text{RC} \quad (4)$$

Here, CR less than or equal to 0.1 is considered acceptable for pairwise comparison results. In this study, CR turned out to be 0.031, which approves the validity of the model.

3.3. LULC mapping and its correlation analysis

Annual LULC maps were generated using the 'Random Forest' machine learning algorithm and applied to Landsat images using Earth Engine prowess. Cloud-free annual Landsat images were retrieved from 2007 to 2022. The Pavagadh solar power park commenced its construction in the year 2017. This way, the considered time period covers the analysis years before and after the onset of the power plant.

Remote sensing serves as a valuable tool for investigating the interrelationships among water, energy, and food systems by providing appropriate data across multiple facets [66]. It can facilitate the evaluation of critical factors such as water availability and quality, agricultural land utilization and productivity, as well as energy utilization patterns. In this study, we utilized remote sensing to examine the nexus between these elements, focusing on specific indicators: surface water cover for assessing water availability, irrigated land cover to monitor agricultural activities, and solar farm area cover to analyze solar power generation. By extrapolating annual land cover area statistics from the generated data, we could discern trends in these activities over time. Furthermore, through correlation analysis, we quantified the degree of influence that each of these parameters exerts on one another within the SAW Nexus framework.

The Pearson correlation coefficient is a statistical measure that measures the linear correlation between two variables. The coefficient ranges from −1 to 1, where 1 indicates a perfect positive correlation, −1 indicates a perfect negative correlation, and 0 indicates no correlation. This method was helpful in determining the relationships within the SAW nexus. Canonical correlation analysis (CCA) is a statistical technique used to identify and measure the relationships between two sets of variables. CCA identifies the linear combinations of variables in each set that are most strongly correlated with one another, and quantifies the strength of these correlations in terms of a canonical correlation coefficient. Required data for the analysis was acquired from ICRISAT, India web portal (http://data.icrisat.org/dld/src/crops.html). It provides a comprehensive collection of agricultural data related to irrigation. The groundwater level information from the India Water Resources Information System (WRIS) website (https://indiawris.gov.in/wris/#/GWProspects) can be very useful in analyzing the relationship. It provided data on the precise location where the GW stations were located in the vicinity of power plants.

3.4. Land suitability map (LSM)

The following parameters were considered as inputs for the preparation of LSM of India, after having discussion with experts from Solar energy sectors: (a) Agricultural Crop-land, (b) PV output potential, (c) Distance from Power Grid, (d) Land Surface Temperature (LST) and (e) Water availability index. The description of each parameter is mentioned in Supplementary Table S1. Vegetation cover and slope more than 11° were masked out, as these areas are considered inappropriate for sustainable solar power development. ESA

World Cover map was used to get vegetation cover class, while slope data was generated using SRTM DEM. The parameters' input values were assigned between 0 and 10 as shown in Supplementary Table S2. Further, criteria weightage derived from the AHP model for each parameter was applied and processed to generate LSM. Speckles and noises were reduced using the Earth Engine neighborhood filtering kernel. Later, the result was divided into 7 layers as can be seen in the final product.

4. Results

4.1. Distribution of solar power plants

India has witnessed the establishment of a multitude of solar plants of varying sizes across the country. The Solar Panel Index (SPI), developed within the scope of this study, offers a robust method for identifying the locations and area coverage of these solar plants via satellite data, as illustrated in Fig. 4. High SPI values distinctly highlight solar farms at four different locations within India. The Bhadla Solar Park (Fig. 4b) in Rajasthan state, primarily an arid region, stands as the world's largest solar park with an installed capacity of 2245 MW [67]. Another notable solar park is the Kamuthi Solar Park (Fig. 4a), situated in the far south of India, in Tamil Nadu state. Other significant solar parks include the Pavagadh Solar Park and the Kurnool Ultra Mega Solar Park, both of which are encircled by agricultural lands.

Map in Fig. 5 shows the locations of solar farms in India in 2020 developed based on the SPI. This innovative method proves highly beneficial in distinguishing solar plants from the surrounding landscapes, even under varying environmental conditions. Solar farms are distributed across the country, with a high concentration of plants found in the states of Haryana, Maharashtra, Karnataka, and Tamil Nadu. Interestingly, despite their high solar power potential as per India's national power portal, no major solar farms were found in the northern regions of Jammu, Kashmir, and Ladakh [68].

4.2. Changes in agricultural land cover

Fig. S1(a) shows the Land Use Land Cover (LULC) map of India in 2005, obtained from the Oak Ridge National Laboratory Distributed Active Archive Center of the National Aeronautics and Space Administration [69]. The map divides the landscape of India into 19 classes (Figs. S1a, b, and c). Because India is an agrarian country, a substantial portion of its land is dedicated to agricultural

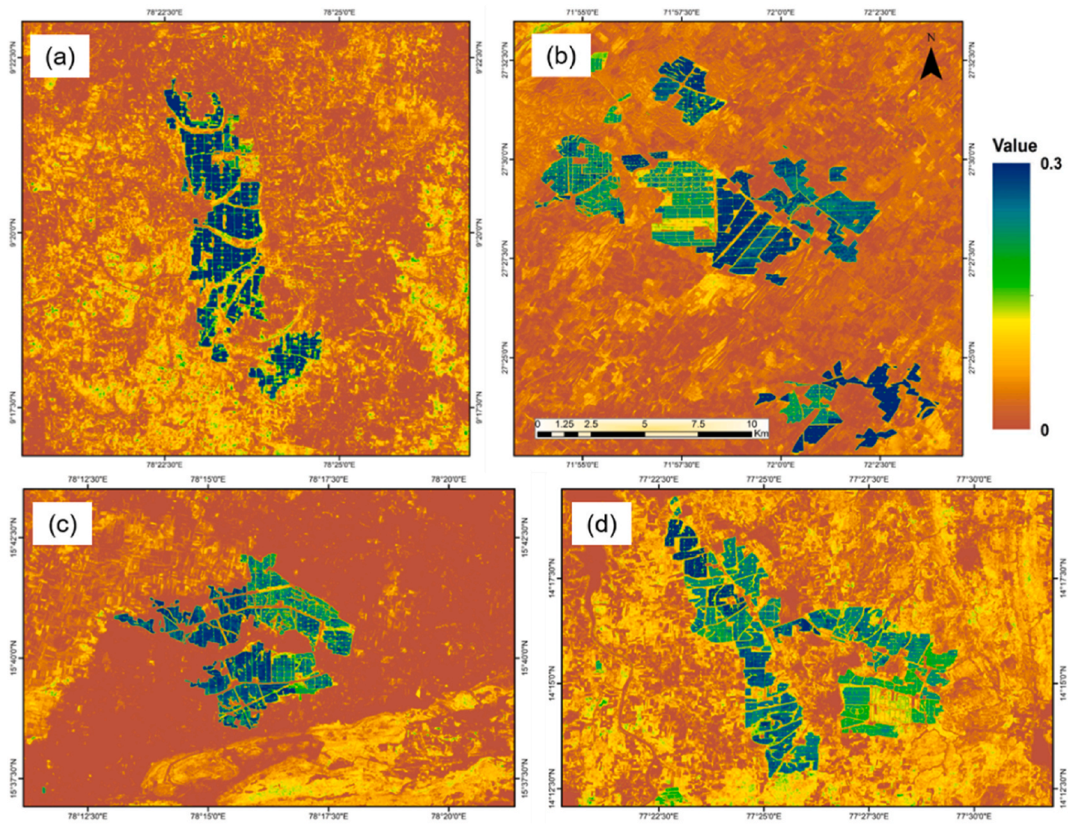


Fig. 4. Raster layer generated using Solar Panel Index (SPI), highlighting solar panels locations at (a) Kamuthi Solar Park, (b) Bhadla Solar Park, (c) Kurnool Ultra Mega Solar Park, and (d) Pavagadh Solar Park.

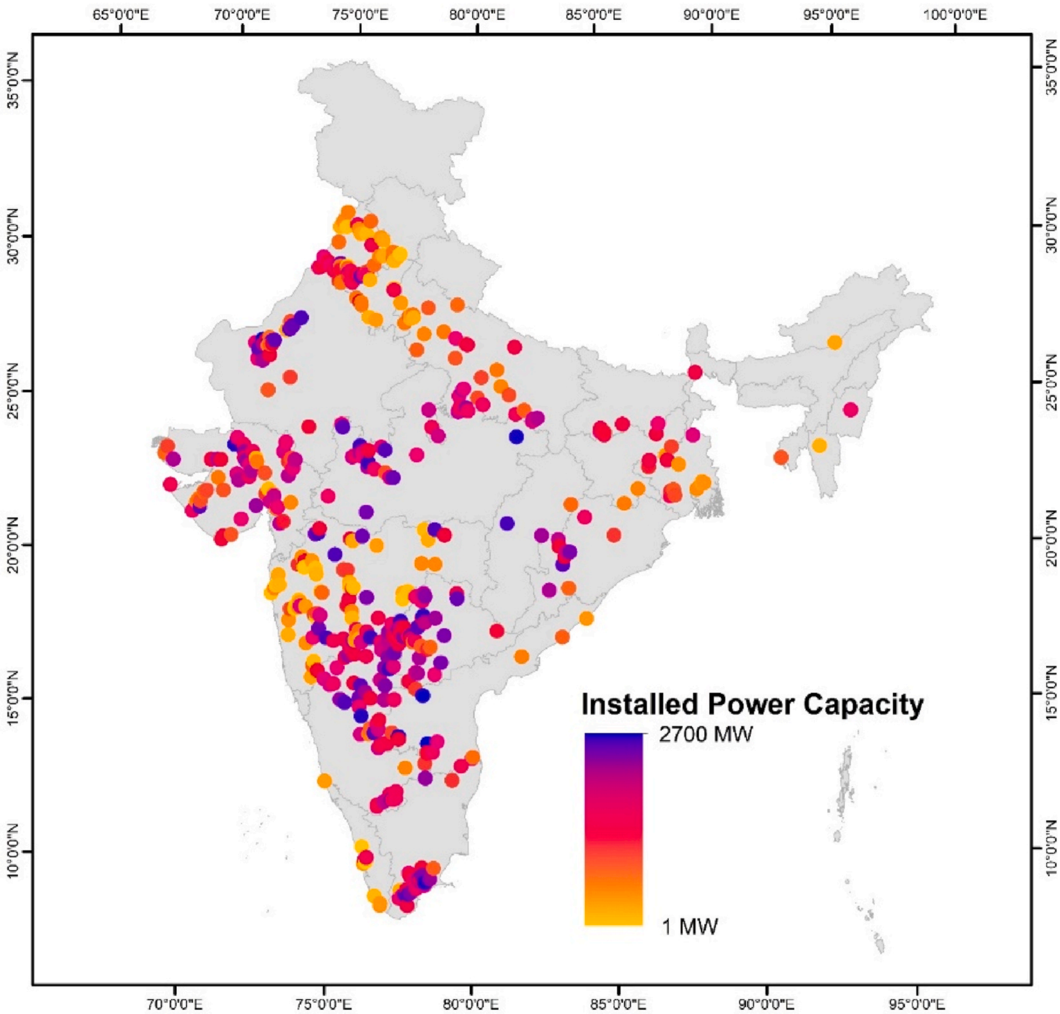


Fig. 5. Geographical distribution of solar farms and their corresponding estimated installed capacities.

purposes. We used this information to analyze changes from agricultural land into solar power plants. Therefore, we projected the identified solar farms onto the LULC map. We found that a large portion of land that is now used for solar farms was previously used for agricultural crops. Fig. 6 presents a state-by-state depiction of Land Use and Land Cover (LULC) changes, measured in hectares, revealing a predominant trend of agricultural cropland conversion into solar plants across virtually all states. The eight states featured in the figure are those with the highest installed solar capacity in the country, collectively accounting for 86.87 % of the nation's total solar power generation [70]. Analyses of LULC maps from previous years, specifically from 1995 to 1985 (Fig. 6b, and c), revealed a similar pattern. This pattern indicates the general trend that agricultural land that was previously used for food production has since become a popular choice for solar energy production, highlighting the encroachment of agricultural land.

In the context of agricultural practices, soil preparation techniques such as ploughing, leveling, manuring, and weeding play a crucial role in maintaining land quality. When land is leased for solar power installations for extended periods, these routine procedures may be neglected, potentially leading to a decline in land quality [71]. The Indian government's "KISAN URJA SURAKSHA EVAM UTTHAN MAHABHIYAN (KUSUM) Yojana" schemes promotes the expansion of solar power, with many farmers choosing to lease their land to companies for periods up to 25 years [72]. The 'Saur Krushi Vahini Yojana (SKVY)' scheme offers attractive financial incentives and straightforward eligibility requirements for landowners, providing them with a stable income source [72]. However, long-term solar panel installation on agricultural land may have unintended consequences on land quality, rendering it unsuitable for future farming activities. The absence of regular soil treatments may result in weed proliferation, which could adversely affect the land's organic content and overall fertility. This potential trade-off between solar energy expansion and agricultural land preservation highlights the need for a balanced and sustainable approach to land use planning in the context of solar power development.

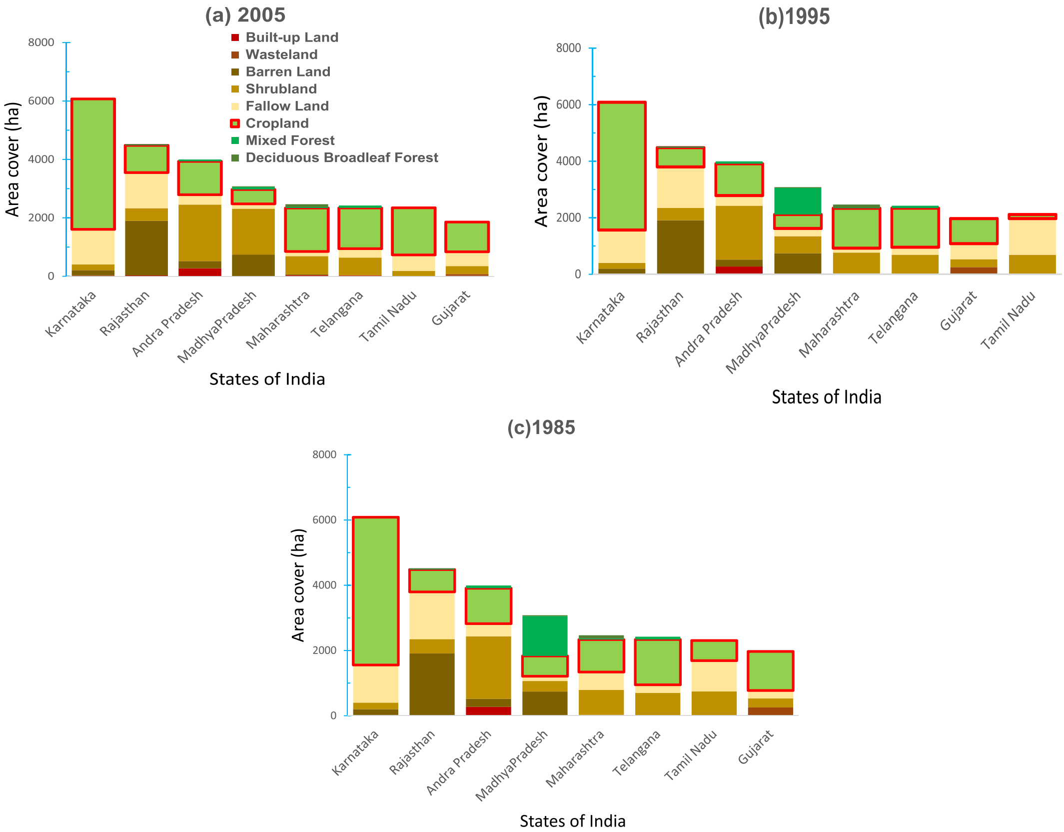


Fig. 6. (a–c). LULC change caused by Solar power plant installation for (a) 2005, (b)1995 and (c)1985 and the states mentioned here are top 8 states with highest solar power installed capacity.

4.3. Water resource availability

When compared with other primary power generation sources such as thermal and nuclear, solar photovoltaic (PV) power generation is significantly more water-efficient. However, the challenge lies in the fact that these solar power plants are often situated in water-stressed areas. The majority of the water requirements for these plants (approximately 60 %) are fulfilled by groundwater accessed via borewells, while the remaining demand is met through surface water sources, including rivers, canals, and lakes [28]. Developers generally prefer to utilize groundwater as it is freely available, resorting to surface water only when necessary, which typically involves reliance on local contractors. In addition to the quantity of water, the quality of water required also greatly influences the actual water usage. For instance, reverse osmosis (RO) treated water is recommended for cleaning solar panels. However,

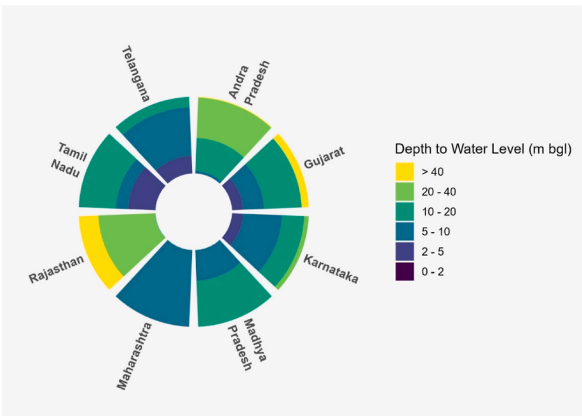


Fig. 7. State-wise groundwater level distribution over solar farms.

the RO process itself results in a significant amount of water wastage. Thus, both the quantity and quality of water are essential considerations in the operation of solar power plants [28]. Access to reliable water resources is critical to the operation of solar power plants. Fig. S2 shows groundwater levels in India, which considerably vary throughout the country because of differences in land type. Projection of the solar farm locations onto the groundwater map revealed that areas with the highest installed capacity are located in regions with low groundwater depths, exacerbating water strain in the area (Fig. 7). Regions experiencing severe ground water scarcity include Rajasthan, Madhya Pradesh, and Andhra Pradesh.

Fig. S3 shows the surface water bodies located throughout India, which significantly governs the water resources availability for human activities. Fig. 8, shows the numbers and percentages of power plants located within a 5-km radius of these surface water bodies. The regions Madhya Pradesh, Maharashtra, and Rajasthan have minimum presence of power plants. In particular, Madhya Pradesh had no power plant located within 5 km of surface water bodies, consistent with our observations regarding groundwater content (Fig. 7). This suggests that solar farms situated in the state of Madhya Pradesh are likely to place a significant demand on regional water resources. Overall, the installation of large solar power plants is exerting increasing pressure on water management conditions throughout the country.

4.4. Land suitability map

Various environmental parameters (Fig. 9) sourced from a variety of references (Table S1) were collected to create a LSM (Fig. 10). These input parameters underwent rasterization and were then standardized to a scale of 0–10, as shown in Table S2. Subsequently, AHP weightage criteria obtained from the AHP model (Fig. S4) were employed to assign importance to these input parameters, ultimately producing the desired LSM output.

Fig. 10 shows a land suitability map (LSM) of India, with seven categories that range from least suitable to most suitable. LSM aims at the sustainability of water resources, and agricultural production in the region. The map is generated based on input from experts at the Rajasthan Renewable Energy Corporation Limited using the analytical hierarchy process (AHP) (Fig. S4), a multi-criteria decision-making model. The LSM map is a high-resolution (100 m) georeferenced raster image of India, which can support future planning in the solar energy sector.

According to the resultant LSM map, Rajasthan state has the highest suitable land availability for solar power generation. The "Most Suitable" land category area comprises more than 70 thousand square kilometers within the state, which is way more than enough for achieving the target of 280 GW by the year 2030. Most of the solar power plants currently located are coming under moderately suitable regions which has 29.6 % cover (Table 1). The "Unsuitable" land category depicted in the figure includes forests and high-slope areas that are not suitable for solar installation. Solar panels installed on slopes have adverse effects on the ecological system. Accumulation of soil mounds from solar panel installation on slopes led to landslides during heavy rain causing destruction in the region [64]. Infrastructure on flat land is preferable.

4.5. SAW nexus in pavagadh solar park

The Karnataka Renewable Energy Development Ltd (KREDL) and the Solar Energy Corporation of India (SECI) founded the Karnataka Solar Power Development Corporation Ltd (KSPDCL) in March 2015 with the intent to inaugurate solar power initiatives in Karnataka [73]. The project spans an expansive area of 5260 ha, encompassing the five villages of Balasamudra, Tirumani, Kyataganacharlu, Vallur, and Rayacharlu [74]. The selection of Pavagada as the project's site was dictated by availability of high solar radiation. Pavagada taluk is located at an elevated plateau in a semi-arid region surrounded by rocky hills, which the state Government had declared as drought-stricken several times in the past 60 years [73].

Solar power plant companies have adopted a practice of leasing land from agricultural landowners instead of buying it outright. This approach enables farmers to maintain ownership of their land while benefiting from a steady stream of rental income. The Pavagadh solar power plant project, however, has raised certain concerns, particularly pertaining to its potential impact on local water

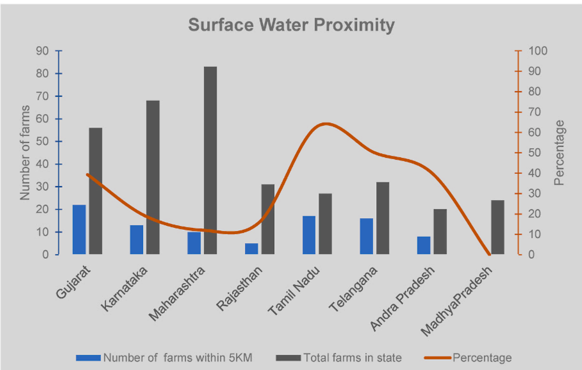
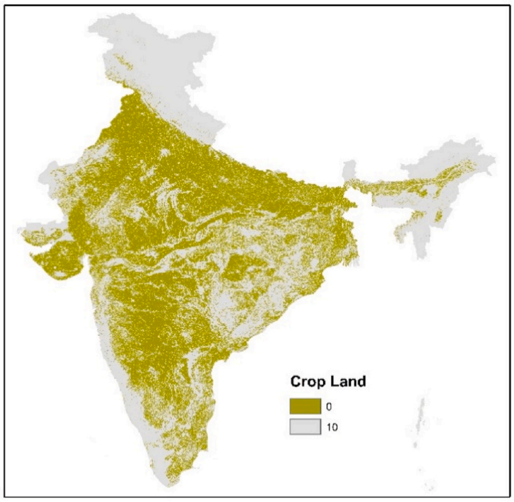
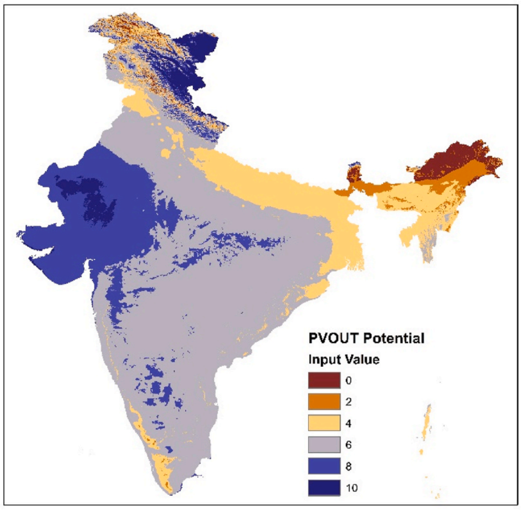


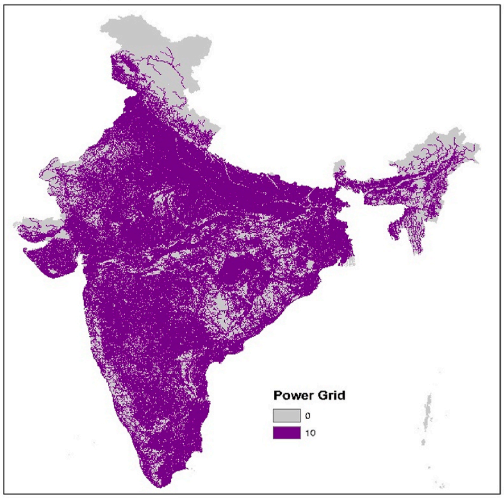
Fig. 8. State-wise distribution of number of Solar farms within the proximity of surface water source.



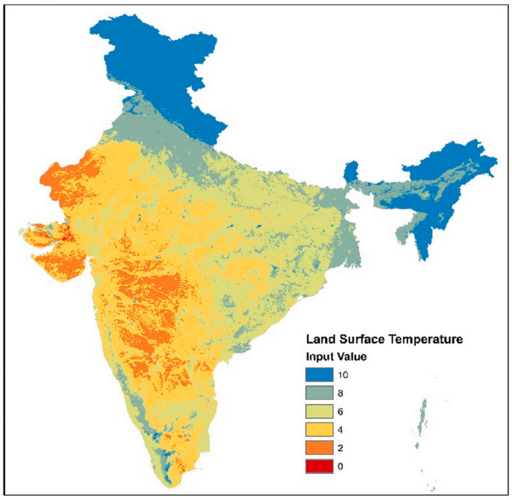
(a) Agricultural crop land



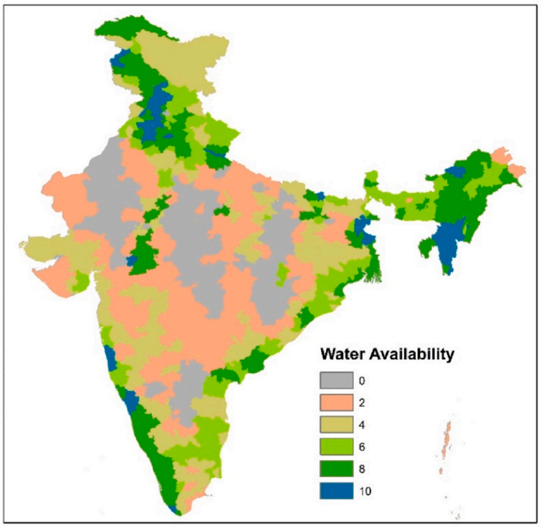
(b) PV OUT



(c) Power Grid



(d) LST



(e) Water availability

(caption on next page)

Fig. 9. Rasterized input environmental parameters: (a) Agricultural Crop Land, (b) PV Output Potential, (c) Power Grid, (d) Land Surface Temperature, and (e) Water Availability.

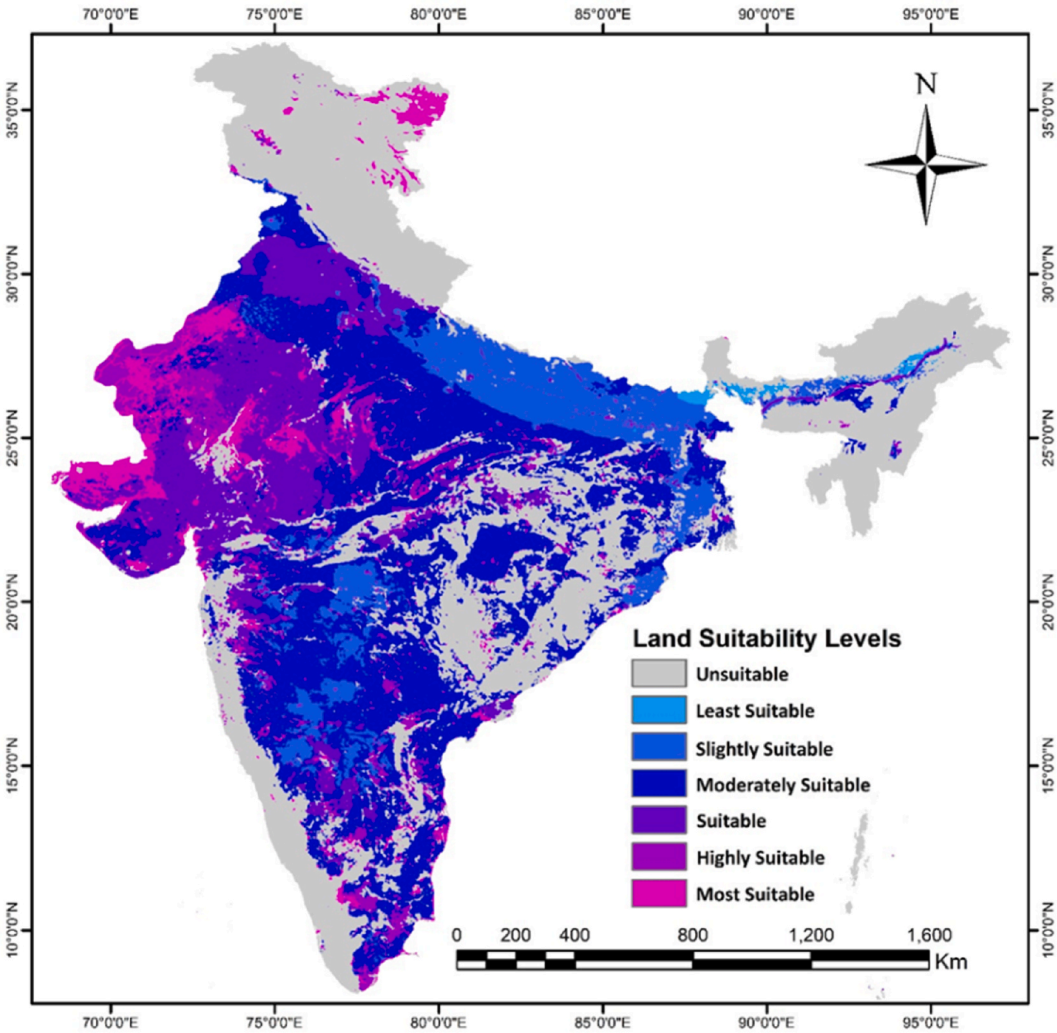


Fig. 10. Land Suitability Map for solar farm installation in the study area.

Table 1
Distribution of currently located solar power plant according to LSM generated from this study.

LSM Categories	Percentage cover
Unsuitable	36.13
Least Suitable	0.42
Slightly Suitable	9.84
Moderately Suitable	29.6
Suitable	13.5
Highly Suitable	5.09
Most Suitable	5.42

scarcity and soil quality [75]. This idea of leasing instead of purchasing land can be seen as a symbiotic relationship, where both the solar companies and the landowners stand to gain. The companies gain access to the necessary land for their operations, while landowners can enjoy a steady income source without relinquishing their ownership rights. However, it is essential that these operations do not intensify local environmental challenges. In the case of the Pavagadh solar power plant, this balance is crucial to ensuring the project's sustainability, as its potential effects on water scarcity and soil quality could significantly impact the local environment and agricultural practices. Therefore, it's crucial that such potential impacts are thoroughly investigated and mitigated to ensure sustainable development.

LULC map (Fig. 11), covering power plant and its surrounding area up to 5 Km boundary extend, includes water body (reservoirs), and cultivated agricultural land. The Pearson Correlation Coefficient was used to assess the strength and direction of relationships between agricultural and hydrological variables and the SAW nexus; this enabled the identification of patterns and trends in LULC classes, along with their implications for solar energy, agriculture, and water management. This approach is an effective method for nexus evaluation [76]. Statistics were derived by tracking the area coverage of LULC classes annually from 2007 to 2022. There was a strong positive correlation between solar power and agriculture (r = 0.877), indicating that the solar power plant is beneficial for surrounding agricultural areas (Table 2). A moderate positive correlation between solar and water (r = 0.205). The result suggests that solar power generation is positively affected by the availability of water in the surrounding areas. This could be due to the fact that solar panels require water for cleaning and cooling, and the availability of water could improve the efficiency of the solar panels [77]. Our results suggest a relationship between LULC classes and their surrounding areas; Agricultural land area, water body extent, and solar power plants expansion benefitted from each other. Using SPI, the LULC classification overall accuracy increased from 81.02 % (Table 3) to 89.72 % (Table 4) with the Kappa coefficient increasing from 0.75 to 0.86 respectively. In all, 253 validation points were recorded with reference to high resolution Google Earth images.

Canonical correlation analysis (CCA) was separately performed at the solar power park. Independent variables were LULC classes, solar power plants, agriculture, and water bodies; dependent variables were the production values in tons for cereals, millets, pulses, oilseeds, fruits, and vegetables in tons, as well as the area of cropped land, canals in hectares, and groundwater level. The parameter with the greatest significance was cereals; its canonical correlation coefficient (r) of 0.8 indicates a strong correlation between cereal production and the LULC classes of the solar power plant, agriculture, and water bodies (Table 5). The R-squared value of 0.64 indicated that the model explained a large proportion of the variation in cereal production. Other parameters (e.g., total cropped area, millets, pulses, and oilseeds) had lower correlation coefficients and R-squared values, indicating weaker associations with LULC classes. However, they remained statistically significant, with canonical correlation coefficients ranging from 0.46 for millets to 0.76 for pulses. Overall, the CCA results suggest that LULC classes, solar power plants, agriculture, and water bodies have moderate to

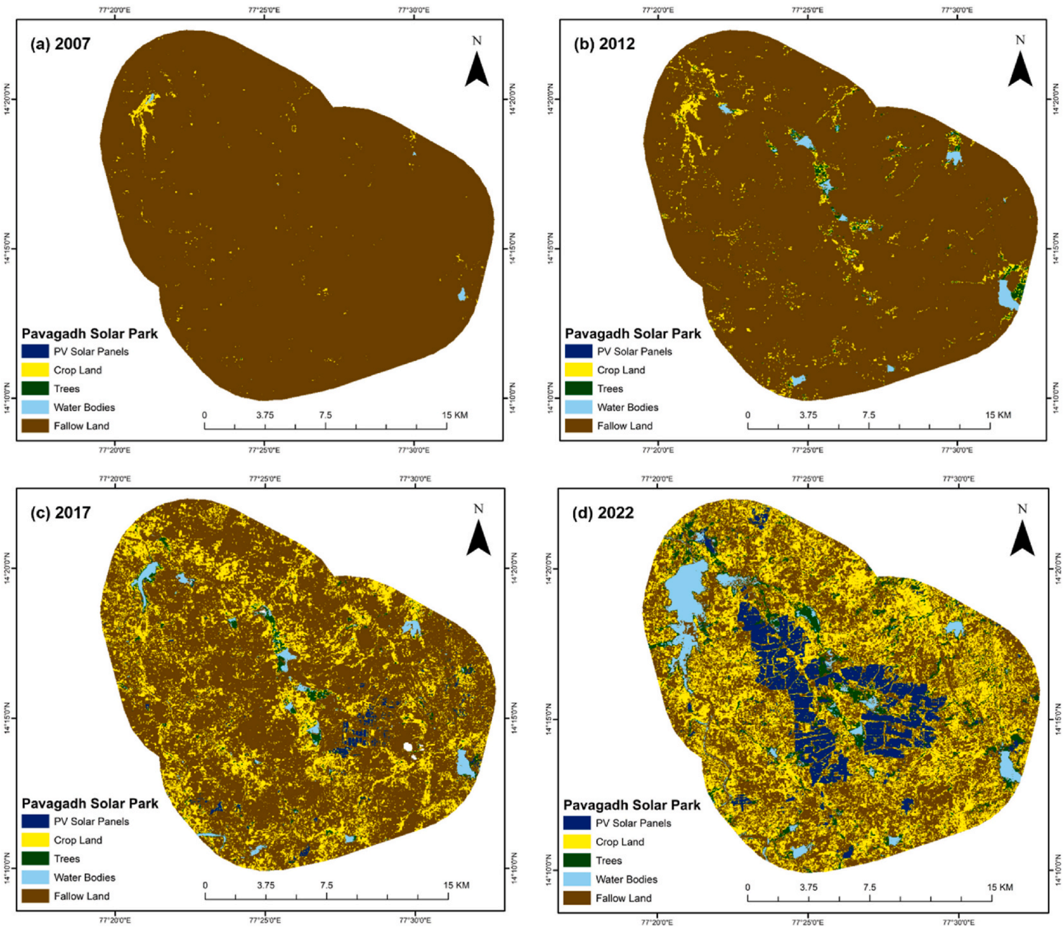


Fig. 11. LULC of Pavagadh solar park area and its surrounding boundary up to 5 km in the years (a) 2007, (b) 2012, (c) 2017, and (d) 2022.

Table 2
Pearson correlation (r) among the classes of nexus.

	Solar	Agriculture	Water
Solar	1		
Agriculture	0.877	1	
Water	0.205	0.052	1

Table 3
Accuracy assessment: validation error matrix without SPI.

	LULC Classes					Producer accuracy
	Solar	Agri	Other	Water	Trees	
Solar	50	0	1	0	0	0.98
Agri	0	43	3	0	3	0.88
Other	6	16	66	0	0	0.75
Water	0	0	0	29	0	1.00
Trees	1	10	5	3	17	0.47
User accuracy	0.88	0.62	0.88	0.91	0.85	
Kappa coefficient	0.75					
Overall accuracy (%)	81.03					

Table 4
Accuracy assessment: validation error matrix with SPI.

	LULC Classes					Producer accuracy
	Solar	Agri	Other	Water	Trees	
Solar	50	0	1	0	0	0.98
Agri	0	47	1	0	1	0.96
Other	0	10	78	0	0	0.89
Water	0	0	1	28	0	0.97
Trees	0	6	4	2	24	0.67
User accuracy	1.00	0.75	0.92	0.93	0.96	
Kappa coefficient	0.87					
Overall accuracy (%)	89.72					

strong relationships with the production values for cereals, millets, pulses, oilseeds, fruits, and vegetables, as well as the area of cropped land, canals in hectares, and groundwater level. This indicates that SAW nexus in Pavagadh solar park has a good influence on the agricultural sector on district level, and groundwater level in the locality. While the insights of the correlation analysis are valuable, it is important to acknowledge its limitations. It can be attributed largely to data scarcity. Further studies with more comprehensive data can provide a more definitive understanding and potentially validate our findings.

5. Discussion

The utilization of land resources is a critical factor involved in planning and building societies. It directly or indirectly impacts the environment, ecology, economy, lifestyle, and other aspects of society. The recent surge in solar plant projects has led to irreversible changes in the environment. The SPI method is an effective technique for mapping solar farms and has great potential for future efforts to achieve continuous monitoring of panels. The method solely relies on optical satellite data and can be easily implemented using widely used Landsat and Sentinel-2 images. The SPI algorithm holds high potential in future for solar power expansion monitoring as it makes easy detection of solar farms using open-source data. We have shown the potential of SPI for creating datasets of solar farm location and estimated installed capacity for the entire India. The application of computer vision algorithms based on high-resolution imagery and aerial photography were used for location of solar panels whereas others focused on mapping of solar power plants using significance of texture [46,47]. Overall, our SPI and other techniques showed their capability for easy detection of solar farms.

The detection and allocation of solar power plant is thought to be good development for a region-specific location but the nexus between solar-argi-water is necessary for sustainable development. Agriculture is at the core of India's economy; it is affected by various factors such as climatic and weather conditions, precipitation, field planning, sowing methods, and plantation orientation. Agricultural land encroachment for the construction of solar power plants has recently increased [78]. Farmers choose to invest in electric power production over food because power production is more profitable. This short-term benefit can have long-term impacts on the food industry. Therefore, it needs on ground information and analysis of soil condition under the solar panel structure. A field visit to solar power plants in Maharashtra (Fig. S5) provided us with an opportunity to collect soil samples and analyze them for any changes. We investigated the microbial populations within the topsoil (0–15 cm) of both solar panel sites and agricultural farms. Typical topsoil microbial communities consist of nematodes and protozoa (10^3 colonies), algae and fungi (10^5 colonies), and

Table 5
Canonical Correlation Analysis (CCA) between the nexus and the parameters.

Parameters	SAW LULC variation			
	Canonical Correlation	R-Squared	F-Value	Wilk's Lambda
Cropped area	0.66	0.44	1.08	0.55
Cereals	0.8	0.64	2.45	0.35
Millets	0.46	0.21	0.36	0.78
Pulses	0.76	0.58	1.87	0.41
Oilseeds	0.76	0.57	1.83	0.42
Fruits and Veg	0.82	0.68	2.91	0.31
GW bgl	0.6	0.37	1.77	0.62
Canals area	0.94	0.88	10.75	0.11

actinomycetes and bacteria (10^7 colonies). The outcomes (Table S3) suggested a significant difference in the concentration of algae and fungi, particularly in the soil beneath solar panels. The expected concentration ranges for these microorganisms are 1–50 and 100–1500, respectively [79]. This observed disparity may be attributed to the damp conditions created under the solar panels, which foster a wet, humid, and anaerobic environment compared to other locations. Such conditions could lead to an increased presence of algae and fungi within the soil [80]. Additionally, we found that the concentrations of nematodes and protozoa in agricultural farms were primarily influenced by the availability of nitrogen, a result of fertilizer application [81]. This nutrient-rich environment promotes microbial activities related to mineralization, including nitrification, denitrification, and ammonification. These findings demonstrate the potential impact of solar panel installations on soil microbial communities and further detailed study is necessary to understand the overall influence of solar structure on soil.

Many regions in India are experiencing water shortages; fluctuations in precipitation and rainfall negatively affect crop production and daily water consumption by society [37]. Similarly, solar farms require water to clean panels effectively; without such cleaning, power plant efficiency declines. In some power plants, water is extracted from groundwater wells (Fig. S5b). In some power plants self-cleaning robots are used. Such robots perform daily operations of cleaning without any external source of water or electricity (Fig. S5c). Another, field visit to Bhadla solar power park, we got to know that, in most solar power plants, water is being transported from the Indira Gandhi Canal. It is located at a far distance from the power plant. While some of the power plants within the parks were using automated cleaning robots, which require no water consumption, and run solely on their own solar power source. This shows the importance of having self-cleaning robots. The application of cleaning robots is an effective choice yet is quite expensive [82]. Hence, some kind of incentive in the use of robots could bring positive change in water utilization.

It is challenging to grant permission for solar power plant installation because such plants can have negative impacts on agriculture and water resources. There is a trade-off among the food, energy, and water sectors with respect to land use. Proper guidelines from a central management body are essential for sustainable planning. Currently, the government determines state-wise solar power potential estimates based on land availability and sunshine. On a broader scale, land type and natural resources should also be considered. Previous studies discuss the use of the Solar radiation zone map prepared by TERI based on the IMD database as an important material for planning [66]. Other studies considered the terrain and infrastructure development aspect for solar power installation [67]. However, all these datasets give a coarse idea of the solar resources available on land. LSM generated in this study provides a high resolution map with 100 m resolution. This map incorporates various sustainability factors, primarily focusing on SDG #2 (Zero Hunger), #6 (Clean Water and Sanitation) and #7 (Affordable and Clean Energy). Additionally, we have taken care to minimize potential impact on other ecologically significant areas like forests. This approach ensures a balanced consideration of multiple environmental and sustainability aspects in our study.

We used CCA to identify the LULC classes most strongly associated with the SAW nexus and agricultural and hydrological variables, then quantified the strengths of these associations. This information helps to understand the significance of the nexus on a larger scale. Previously CCA proved as an important method to observe the interaction between LULC classes and variable parameters [83]. It gives an idea of the importance of the SAW nexus and its influence on society. Eventually, it can facilitate the establishment of strategies to optimize the use of these resources in accordance with sustainable development and energy security policies. A more detailed study is required to evaluate the interaction within the nexus.

5.1. Policies to promote sustainable resource management in SAW nexus

Stringent laws have shown an overall positive effect on carbon emission and sustainability [84]. The policies need careful study and implementation to ensure a sustainable future. The approach should be comprehensive, considering interdependencies and trade-offs between sectors, with a focus on optimizing resource use, minimizing waste, and boosting resilience. The following policies are recommended to promote sustainable resource management.

I. Encouraging integrated planning approaches that take into account the interdependencies between water, energy, and food systems, and promote collaboration among stakeholders.
II. Promoting education and awareness among stakeholders, such as farmers, policymakers, and the general public, about the benefits of sustainable resource management in the solar, agriculture, and water nexus.

III. Developing regulatory frameworks that promote sustainable resource management practices, such as water-use permits or energy efficiency standards for buildings.
IV. Establishing land leasing agreements with solar developers that prioritize non-agricultural land, such as barren land or degraded forests, for solar development to reduce pressure on agricultural land.
V. Implementing water pricing policies that reflect the true cost of water use, including the cost of treatment, distribution, and environmental impacts. This can encourage solar developers to use water more efficiently and promote sustainable water management practices.
VI. Promoting and incentivizing use of robotic cleaning systems for solar panels that can replace water usage and cut-short labor cost.

This approach can support economic growth and social development in the solar industry. By taking a comprehensive and integrated approach to resource management, it is possible to achieve a more sustainable and equitable future for all stakeholders involved in the solar, agriculture, and water nexus. Implementing rigorous policies of this nature can effectively prevent land encroachment in other countries too [85–87]. By enacting effective water management policies and offering incentives for the deployment of cleaning robots, with proactive steps can have control over the water resources, thus mitigating potential stress and scarcity issues [10,88–90]. These policies can help to balance the needs of different stakeholders and promote the sustainable use of natural resources, while also supporting economic and social development goals.

6. Conclusion

This study introduces a novel Solar Panel Index (SPI), using multiple spectral bands to accurately identify solar panels, and attains an 89 % accuracy in Land Use and Land Cover (LULC) classification. This index has aided in creating a detailed map showing the locations and capacities of solar farms nationwide, valuable for energy distribution planning. Our findings show that over 40 % of solar power plants are built on lands previously used for agriculture. We also analyzed water availability around these areas, emphasizing the crucial relationship between solar installations, agriculture, and water—referred to as the solar-agriculture-water (SAW) nexus—in sustainable development. Field visits and expert consultations enriched our understanding of the operation of solar power plants and their impact on natural resources and provided insights into the intricate relation between solar energy, land use, and water management. We developed a high-resolution (100 m) Land Suitability Map (LSM) for India, focusing on the SAW nexus, which is a potential tool for informed land-use planning, keeping in mind the intertwining of solar energy, agriculture, and water. Rajasthan emerged as an optimal region for solar installations from our analysis. This research proposes policy guidelines to aid the sustainable development of the solar energy sector while addressing SAW nexus-related challenges. Implementing the insights and suggestions from this study can help balance resource demands effectively and foster the sustainable growth of the solar sector. In conclusion, considering the SAW nexus in land and solar plant planning is vital. A well-rounded approach can guide stakeholders in making decisions that support the harmonious development of solar energy, agriculture, and water management, paving the way for balanced resource use and sustainable growth in the solar energy sector and regional development overall.

Data availability

Data will be made available on request.

CRediT authorship contribution statement

Hitesh Supe: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Writing – original draft, Writing – review & editing. **Abhishek Abhishek:** Supervision, Writing – review & editing. **Ram Avtar:** Conceptualization, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e23125.

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