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Agrivoltaic Farming: Synergizing Solar Energy Generation and Agricultural Production

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***Abstract*— Population expansion and rising needs for clean energy, food, and water put increasing strain on agricultural land in many developing nations, necessitating the quick development of innovative, holistic, and climate-compatible solutions. A global grand challenge is to provide a sustainable supply of food, energy, and water resources in the face of increased pressures from climate change. In this research paper, the main aim is to maximize land use, while maximizing crop production and solar energy i.e., to build such an algorithm which provides a pattern for the field if someone wants to make patches in the field for crop production and for solar panels as well. To get a sight, firstly a big canvas is created using the OpenCV library which represents the field, and 2 other small dimension images were created using the Python library PIL (Python Imaging Library). The main aim is to fit the 2 smaller dimension images into a big canvas while making maximum utilization of space in a big canvas and also maximizing the use of 2 small dimension images. To get the desired result several algorithms are tested in line to check their efficiency. A few of the algorithms only stood up to an average efficiency and were able to give a result which can justify the research paper requirement.**

***Index Terms*— Agrivoltaic, OpenCV, PIL (Python Imaging Library), Algorithms**

I. INTRODUCTION

According to preliminary assessments of the United Nations Task Team for the Global Crisis Response Group14, the impact of the COVID-19 pandemic and the Ukrainian war on food, energy, global commodity, inflation, and financial markets over the past two years has resulted in a sharp increase in food and energy prices. The unfolding effects of climate change and the resultant decrease in agricultural output mean that food and energy insecurity are increasing fast around the planet. Agrivoltaic (AV) systems, which apply power resources to provide agriculture production, such as facility gardening, facility breeding, and characteristic pastoral construction, can be a solution to food and energy issues. In this research paper main objective is to create a new mode of production of "farming + power generation + agricultural production activities" that will be the future of farming if humans want to avoid food and resource scarcity. Since 1980, there has been debate about the concept of Agrivoltaic (AV), however, it was rarely mentioned until the beginning of the millennium. Indeed, relevant research groups in China, France, India, Portugal, and the United States conducted research on the application of solar energy in agriculture as early as the 1960s, including agricultural products and wood drying, air conditioning in breeding sheds, and so on. The efficiency of land usage is a major impediment to the coordinated development of the solar and agricultural industries. AV can achieve the combination of some beneficial resources, boost agricultural development through diverse forces, and increase resource usage efficiency. Same task i.e., usage of land for agricultural activities as well as for electricity production is the main objective of this research paper. To obtain the objective, first of all, several heuristic algorithms were tested to check their efficiency for the desired problem. Heuristic algorithms are used when finding an optimal solution is difficult or computationally expensive. Finding an optimal solution for the problem is difficult as the solution required for this paper varies if the size of the land and solar panel increases or decreases. Since finding an optimal solution is difficult, so several heuristic algorithms are tested to check their accuracy and efficiency such as Greedy Algorithm, Genetic Algorithm, Sky-Line Algorithm. A few other algorithms are also tested but none of them stood in the race to match the requirement of the paper. Only the algorithms named above stood to an extent and provide a sight to find a more accurate and more efficient algorithm for this research paper.

To test the algorithms listed above several tools were used using Python Programming Language. To get a sight and for the visualization part, OpenCV is used to do the pre-processing part for the images like image resizing. Also, a Python library NumPy is used to create some blank images to check the model accuracy

II. LITERATURE REVIEW

Harshvardhan and Joshua [1] state that the co-development of land for solar PV electricity and agriculture, provides a solution to the conflicting demands for food and renewable energy on available land. Through simulations employing the STICS (Simulateur multi-disciplinaire les Cultures Standard) crop model for agriculture and PVSyst (Photo-voltaic production) for solar energy production. The combined benefits of solar electricity and shade-tolerant crops show that agrivoltaic farms have an increased economic worth of 30% when compared to conventional agriculture, according to the results. Crops that can tolerate shade reduce output losses and keep commodity prices stable. Even lettuce production might be converted to agrivoltaic systems, increasing national PV generation by 40–70 GW (Giga Watt). Agrivoltaic potential needs to be evaluated globally, taking regional and crop variances into account. This strategy appears to be a potential way to handle issues with land competition, enhancing food security, and agricultural, and energy production all at once. Makoto and Tetsunari [2] mentioned that Akira Nagashima launched agrivoltaics development in Japan in 2004, focusing on small-scale installations of less than 0.1 hectares. These installations have generated approximately 500,000 to 600,000 MWh of power, accounting for approximately 0.8% of Japan's photovoltaic output in 2019. With over 120 crops grown, over 69% of cases had crop modifications following agrivoltaic adoption, raising worries about disrupting established markets. In Japanese agrivoltaics, shading rates range from 10% to 100%, with a median of 30% to 40% determined based on crop light saturation. High shading rates are frequently chosen to enhance electricity sales profit, which may surpass agricultural yields. Notably, the Feed-in Tariff (FIT) policy beat the Renewable Portfolio Standard (RPS), increasing Japan's renewable energy production by 76% between 2012 and 2019, including a spike in solar energy. Prannay et al. [3] state that the increasing growth of land-based solar photovoltaic (PV) farms can clash with agricultural activities. Agrivoltaics, which involves codeveloping land for both solar PV and agriculture, offers a solution. This study looks into the viability of installing agrivoltaic systems on existing grape fields in India in order to optimize PV generation while minimizing agricultural output. A techno-economic analysis investigates the installation of PV systems between trellises on these farms by leveraging grapes' shade tolerance. The study assesses the potential energy generation and economic benefits of various design possibilities. According to the findings, installing the proposed agrivoltaic systems might increase the economic value of grape fields by more than 15 times over conventional farming while maintaining grape production levels. This strategy might generate over 16,000 GWh of electricity on a national scale. Takashi and Akira [4] demonstrate a study whose main aim is to evaluate the efficacy of agrivoltaic systems, which integrate crop production with electricity generation on fields using stilt mounted photovoltaic (PV) panels. As the number of PV power stations grows, the rivalry for land between food cultivation and renewable energy production grows. However, the findings of this study suggest that the stilt-mounted agrivoltaic system can ameliorate the trade-off between crop yield and clean energy output, especially with shade-intolerant crops like corn. The experiment was carried out on a 100-m2 test farm with three sub-configurations: no modules (control), low module density, and high module density. Corn was planted at a density of 9 stalks/m2 and 0.5 m apart in each setting. Corn stover biomass in the low-density configuration outperformed the control by 4.9%, while corn yield per square meter increased by 5.6%. These findings should encourage traditional farmers, clean energy producers, and politicians to explore agrivoltaic systems as a viable alternative.

Hassan and Muhammad [5] addresses the global challenge of preserving food, energy, and water resources while coping with climate change is critical. Innovative and holistic solutions are urgently needed in nations such as Pakistan, where population growth and demand for clean energy, food, and water are straining agricultural land. This work adopts an integrated electrical-optical-thermal model to examine the potential of east/west (E/W) vertical bifacial photovoltaic (PV) farms as advanced agrivoltaic (AV) systems. AV blends solar energy generation with crop cultivation, providing a means to overcome barriers to solar energy expansion while assuring food-water-climate security. In terms of energy output and ground irradiance for crops, the study compares E/W vertical bifacial PV farms to north/south (N/S) tilting bifacial PV farms. The findings show that optimized E/W vertical bifacial PV farms provide homogeneous crop light dispersion. Furthermore, these farms are resistant to soiling, which may reduce water usage, making them good candidates for AV systems, particularly in water-stressed areas. According to this study, E/W vertical bifacial PV farms have promise for long-term energy and agricultural development. Carlos and Alessandra [6] show concerns about land use, landscape changes, biodiversity, ecosystems, and human well-being have arisen in reaction to the increased demand for photovoltaics as a critical component of several countries' energy transition policies. This has resulted in the establishment of novel methodologies and market segments based on integrated perspectives. Among these options, agrivoltaics stands out as a highly promising solution, providing benefits in the food-energy-water nexus at the same time. Demonstrative initiatives are increasing around the world, and insights into various design solutions suited for scaling up to commercial levels are being acquired, mostly due to efficiency concerns. This study conducts a critical review and evaluation of the current technology and spatial design possibilities, employing a rigorous and thorough analysis based on the most recent field knowledge. The study presents a comprehensive methodology based on design and performance metrics, allowing for the identification of the fundamental characteristics of agrivoltaic systems from a multidisciplinary standpoint. Meagan and Aritra [7] state that as the increasing number of countries pledge to achieve net-zero emissions by 2050, there has been a rush in research into the combination of photovoltaics (PV) with agriculture, spawning a new subject known as agrivoltaics (AV). The Land Equivalent Ratio (LER) is an important statistic in this field that has allowed researchers to develop techniques for improving the performance of agrivoltaic systems. To further understand the elements influencing optimization, researchers looked into novel technical technologies like PV tracking and next-generation PV cells. The review also looked at different AV farm layouts, examining how different criteria like distance, height, and density affect shadowing patterns beneath the panels. This in-depth analysis synthesizes research from the last five years, shining light on AV optimization and its far-reaching implications for future AV improvements.

Jerome et al. [8] demonstrate that agrivoltaic systems provide a one-of-a-kind chance to maximize the use of building rooftop spaces. When combined with urban farming, these systems improve microclimate conditions, which improves the performance of solar photovoltaic (PV) systems. PV efficiency is increased by lowering operating temperatures. We discovered that, from 0800 h to 1800 h, PV temperatures in plots with crops beneath the PV system were consistently 2.83 °C and 0.71 °C lower on sunny and overcast days, respectively, when compared to plots without crops. As a result, we expect PV efficiency to improve by 1.13-1.42% on bright days and 0.28-0.35% on overcast days. The reduction in ambient temperature was driven by evaporative cooling, which was attributed to crops beneath the PV canopy, according to findings from a physical agrivoltaic prototype. Furthermore, actual data acquired from the agrivoltaic prototype revealed a 3.05-3.2% increase in energy generation throughout the day when compared to a control system without crops. This demonstrates the beneficial effect of crop presence on overall system performance. The collaboration of urban farming and PV systems demonstrates a

promising option for sustainable energy generation and microclimate improvement. Sangik et al. [9] present a study which states that by combining photovoltaics and agriculture, Agrivoltaic systems (AVS) hold great promise for meeting global renewable energy and environmental demands. Despite empirical evidence of better land use efficiency, AVS adoption is hampered by the lack of standardized models and design requirements. This study fills that need with a thorough AVS design that considers agronomic issues as well as structural safety. To correspond with practicalities and customer preferences, a variety of design styles were investigated, considering photovoltaic module arrangement and customizable circumstances. Safety criteria were developed, considering disaster resilience as well as trade-offs between shading, electricity generation, and construction. The safety assessment indicated that columns are vulnerable to wind loads, with standards varied depending on column spacing. The findings show that this thematic focus is a rising study subject, with a recent concentration, indicating ongoing investigations. Notably, specialist agrivoltaic conferences are an excellent source of current information, with a substantial number held in the United States and China. Recent trends highlight several agricultural aspects. However, the research focuses primarily on short-term forecasts, with no consistent evaluation framework for various predictive analyses. The evaluation of these prediction systems remains difficult, highlighting the field's developing character.

Hideki and Seiichi [10] present the fact that the growth of photovoltaic installations has caused a land-use conflict, pitting power demand against food production demand. Agrivoltaic systems (AVSs) provide a potential solution by increasing land use efficiency while producing electricity and food at the same time. However, in Japan, the installation of over 2000 AVSs has resulted in unfavorable results, posing new issues. This research presents a regionally suitable AVS installation strategy that regulates the scale of AVS implementation to reduce hazards. By integrating into industrial clusters, these initiatives have also boosted local economies. The results showed that the selected rural area has an AVS generation potential equivalent to 215% (17.8 GWh) of the region's yearly energy consumption, using public data and geographic information systems for quantifiability and practicality. Alexis et al [11] developed an idea of strategic usage of land for both solar photovoltaic (PV) electricity generation and agriculture, providing a viable answer to land rivalry while efficiently satisfying energy and food demands. This research looks at the environmental impact of a novel pasture-based agrivoltaic approach that combines rabbit farming with solar PV. This integrated idea is compared to separate rabbit farming and PV production, as well as separate rabbit farming and traditional energy production, in a life cycle assessment (LCA). The IPCC 2013 global warming potential and fossil energy demand techniques were used in the LCA. When compared to alternative scenarios, the pasture-based agrivoltaic system produces the least greenhouse gases (3.8 million kg CO_2 equivalent) and consumes the least fossil energy (46 million MJ) per cumulative MWh of electricity and kg of meat produced over 30 years. When compared to non-integrated approaches, this methodology provides exceptional synergy, reducing emissions by 69.3% and fossil energy usage by 82.9%. These findings highlight the potential of agrivoltaic systems to dramatically reduce environmental impacts, stressing their superiority over conventional approaches in terms of emission and energy intensity. This study supports the need for more widespread agrivoltaic system development.

Hassan et al. [12] state that agrivolatics is an emerging synergy of solar photovoltaic (PV) and agriculture. To maximize output, the optimal design of agrivoltaic systems relies on expert sunlight distribution between crops and PV panels. This research looks into the best single-axis tracking techniques for agrivoltaics, with the goal of properly balancing sunshine distribution between PV panels and crops. These techniques are used for bifacial panel arrays in two PV orientations: East/West and North/South. The study introduces customized sun tracking systems by using models that account for crop shadowing and photosynthetically active radiation (PAR) requirements. Throughout the day, these dynamic schemes shift between regular and reverse sun tracking to meet crop needs. PAR falls below crop demands in the early morning and late afternoon but exceeds them around midday. The study considers seasonal fluctuations, demonstrating a nuanced technique for increasing agrivoltaic efficacy and reinforcing its potential as a unique food-energy-water solution. Aidana et al. [13] present that agrivoltaic systems combine agricultural crop production and energy generation on the same piece of land, emphasizing the dual-purpose use of space. This article conducts a bibliometric analysis of agrivoltaic topics, utilizing SCOPUS indexed publications on economic evaluations of agrivoltaics, agrivoltaic systems for crops and livestock, photovoltaic greenhouses, open-field agrivoltaics, and location-specific analyses incorporating agrivoltaic concepts. For data assessment, the analysis used bibliometric tools such as R Studio and Bibliophagy. In the end, 121 relevant publications were located and examined. Daisuke et al. [14] demonstrate a study that states that climate change and rising food demand necessitate prompt global action. The agrivoltaic method, which involves mounting solar panels above agriculture, provides a twofold answer to these problems. However, present methods frequently impede agricultural output and cause harvest delays owing to solar panel shade. This delay reduces farmers' income, particularly those who rely on timely produce sales. To solve this, a model incorporating solar irradiation-based estimation of energy generation is presented. By taking agricultural productivity and electricity generation into account, this model estimates the ideal cultivation start date for solar-panel-covered crops, ensuring timely harvests and calculating farmers' income.

III. Proposed Methodology

To obtain the desired solution for the paper, Heuristic algorithms are applied. A heuristic algorithm is a problem-solving strategy that employs a practical and intuitive manner to identify approximate solutions when standard methods are either too time-consuming or impractical. Heuristics are frequently utilized when finding the precise solution is computationally impossible due to the complexity or magnitude of the problem. Heuristic algorithms direct their search for solutions using informed guessing and domain-specific knowledge. Heuristics emphasize speed and practicability over optimality, making them especially valuable for resolving complex issues in a variety of domains. Some of the key characteristics of the Heuristic algorithm are:

A. **Speed and Efficiency:** Heuristic algorithms try to create "good enough" solutions rapidly without thoroughly examining all alternatives. They prioritize discovering answers in a reasonable amount of time, even if they are not guaranteed to be optimal.

B. **Iterative Improvement:** Many heuristic algorithms employ iterative procedures to gradually refine results, making minor tweaks in each iteration to increase solution quality.

C. **Domain-Specific:** Heuristics are frequently adapted to specific problem domains, making good conclusions by leveraging domain knowledge or features.

D. **Rules of Thumb:** To guide the search process, heuristics frequently apply rules of thumb, educated guesses, or commonsense tactics. These guidelines aid in narrowing the solution space and prioritizing certain solutions.

In this paper, several Heuristic algorithms were tested to obtain the optimal solution for the desired problem. Some of the Heuristic algorithms are listed below with their efficiency for the problem and how well these models have performed:

A. Greedy Algorithm

Greedy algorithms make locally optimum decisions at each stage in the hope of arriving at a globally optimal solution. They frequently perform well for challenges in which the best immediate solution also adds to a good overall solution. They may, however, not necessarily give the best overall result. For instance, the "Knapsack Problem" can be solved by employing a greedy algorithm that selects objects based on their value-toweight ratio. In this research paper also, the greedy algorithm is tested to check the efficiency and to get the desired solution. Instead of giving a complete and perfect solution in real-world scenarios, greedy algorithms are more focused on the value-toweight ratio. As this research paper is not focused on the valueto-weight ratio problem, instead the main objective is to find the optimal solution based on a given land area with solar dimensions. To apply the greedy algorithm a big field image is taken into consideration and two other images of smaller size were taken. Both the smaller images were resized to a specific dimension to check if the greedy algorithm will be able to fit the smaller images into the big field image with the maximum number of smaller images and to occupy the maximum space of the big field image. For visualization purposes, OpenCV is used to display the pattern and to see the space utilization. Overall Greedy algorithm performs well and gives an accuracy of 70 per cent i.e., makes equal use of both the smaller images and covered 70 per cent area of the big field, but was not able to provide the optimal solution. The accuracy of the model is calculated by finding the percentage of the given area to the area covered by the algorithm while filling the image with smaller images. In search of optimal solution, several other algorithms were tested based on the heuristic approach.

B. Genetic Algorithm

Genetic algorithms are inspired by the process of natural selection. Genetic algorithms entail developing a population of potential solutions and then evolving and enhancing these solutions through processes such as selection, crossover, and mutation over generations. In optimization issues and search spaces with a huge number of options, genetic algorithms are widely used. Genetic algorithms offer a versatile and robust solution to complicated optimization issues. They effectively explore huge solution spaces to identify high-quality solutions by replicating the evolutionary process of selection, crossover, and mutation. In this research paper Greedy algorithm was also tested to check the efficiency of the algorithm. The tools, method and objective to use the genetic algorithm are the same as in the Greedy Algorithm i.e., to check the robustness of the algorithm to address the challenge.

However, the genetic algorithm is neither able to provide an optimal solution nor perform well for the given challenge and provides an accuracy of only 30 to 35 per cent. This percentage of accuracy is below the average accuracy and also below than average efficiency which is required for the challenge. So, in general, a genetic algorithm is considered a failure for the given challenge.

C. Best Fit Rectangle Algorithm

The best-fit rectangle algorithm is a heuristic method for packing a collection of rectangles into a bigger enclosing rectangle. This method seeks to minimize wasted space while maximizing container area use. It is widely used in situations where things of varying sizes must be optimally packed together, such as 2D bin packing, layout planning, and resource allocation. The algorithm works with a set of rectangles, each of which has a width and height. These rectangles must be inserted into a larger container. The container consists of a bigger rectangle that holds the smaller rectangles. The goal is to arrange the smaller rectangles within the container while leaving as little vacant space as possible.

In this research paper Best Fit algorithm performs best out of all the algorithms tested to check the efficiency for the given challenge. The Best fit algorithm populates all the space of the big field with two small rectangle shapes. It fills all the space with the given small images and gives the best results. However, the only disadvantage of the best-fit algorithm is that it comes into play only if the given challenge is based on the shape of a rectangle.

In this research paper, the best-fit algorithm performs best in case of accuracy and efficiency. The only disadvantage that comes into play while applying the best-fit algorithm is that even after filling the field space to a maximum amount if there is some space left in the field then this algorithm keeps on putting rectangles in the field and it crosses the boundary or the limit of the field.

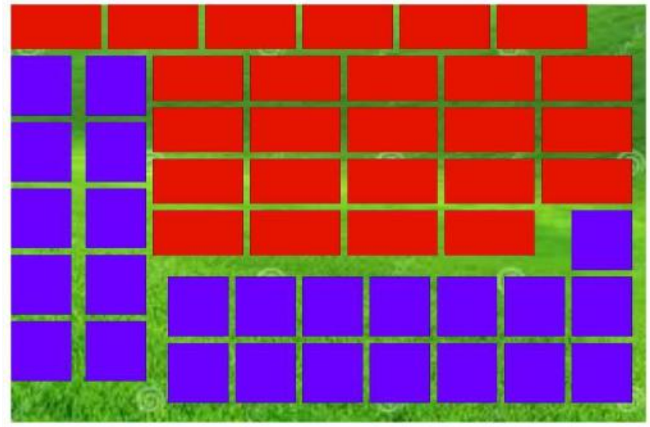

Fig 1. Output of Best -fit Algorith**m**s

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IV. RESULTS

In this research paper, several heuristic algorithms have been followed to get the desired solution to the challenge like the Greedy algorithm, Genetic algorithm, and Best-Fit Rectangle algorithm. Every algorithm is tested and evaluated on the basis of efficiency and accuracy. Out of these three algorithms tested, the Best-Fit Rectangle algorithm performs best and gives the prime solution but still fails to provide the optimal solution for the challenge. The main aim of this research paper is to find a solution which maximizes the use of both small images and the maximum use of the space of big fields.

V. CONCLUSION

The Best-Fit Rectangle algorithm performs best in case of accuracy and efficiency. However, there is still space to find the optimal solution for the problem if the field is of irregular shape because while dealing with irregularly shaped fields, the Best-Fit algorithm's limits become clear since its effectiveness shines most brightly when handling problems with rectangular shapes. Because of the inherent complications provided by non-rectangular borders, the algorithm's performance tends to suffer in such circumstances. As a result, there is a potential to investigate more adaptable solutions customized to irregular shapes, effectively maximizing field utilization and resource allocation.

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