Xi'an Shiyou Daxue Xuebao (Ziran Kexue Ban)/
Journal of Xi'an Shiyou University, Natural Sciences Edition
ISSN: 1673-064X
E-Publication: Online Open Access
Vol: 67 Issue 10 | 2024
DOI: 10.5281/zenodo.14058667

GEOSPATIAL INSIGHTS INTO SUGARCANE CULTIVATION: COMPARING FAO SUITABILITY WITH LOCAL TRENDS IN PUNJAB, PAKISTAN

JAHANZAIB SOHAIL RANA
University of the Punjab, Pakistan.

SAJID RASHEED AHMED
University of the Punjab, Pakistan.

ATHER ASHRAF
University of the Punjab, Pakistan.

FAHD RASUL
University of Agriculture Faisalabad Pakistan.

Abstract

This study provides a comprehensive geospatial analysis of sugarcane cultivation in Punjab, Pakistan, comparing the FAO suitability assessments with local agricultural trends. Utilizing satellite imagery, GIS tools, and climate data, the study identifies key areas of discrepancy between global suitability models and local practices. The findings reveal that while the FAO assessments provide a broad understanding of suitable cultivation zones, local trends often diverge due to socio-economic and infrastructural factors. Therefore, in this research current sugarcane cultivation patterns are assessed and compared to the FAO Recommended Sugarcane Suitable Area (RSSA) to analyse how much current crop practices are diverted from suitability regions. The research findings indicate that the FAO recommended suitable zone for sugarcane cultivation covers 1,745,713 acres, whereas only 637,230 acres are followed by farmers. Which is only 3.3%. Indicating that most farmers grow sugarcane in unsuitable areas. 529037 acers where FAO not recommended but farmer grown, 1687143 acers where FAO recommended but farmer not grown. Historical trend analysis identifies districts deviating from FAO recommendations, affecting crop yields. Eight districts consistently exceed the baseline, seven fall below it, and three have inconsistent behaviour. This research underscores the need for localized agricultural strategies that align more closely with ground realities. The implications of this study are significant for policymakers and agricultural planners aiming to optimize sugarcane production in Punjab.

1. INTRODUCTION

Sugarcane (Saccharum officinarum) cultivation is a vital agricultural activity in Punjab, Pakistan, contributing significantly to both the regional and national economy. As one of the world's top five sugarcane producers, Pakistan cultivates this crop over approximately 1.2 million hectares, especially in the hot and humid regions along the Indus River plains (USDA, 2021a).

Sugarcane (Saccharum officinarum) cultivation is a vital agricultural activity in Punjab, Pakistan, contributing significantly to both the regional and national economy. As one of the world's top five sugarcane producers, Pakistan cultivates this crop over approximately 1.2 million hectares, especially in the hot and humid regions along the Indus River plains (USDA, 2021b).

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Sugarcane serves multiple roles beyond sugar production, including bioenergy, ethanol, livestock feed, and fiber materials (Farooq & Gheewala, 2019), making it a crucial component of the nation's agriculture and industrial sectors. The importance of sugarcane extends globally, as it is one of the most economically valuable crops, serving as a critical raw material for the food, beverage, and bioenergy industries(Shyamal S. Virnodkar et al., 2020) (Chen et al., 2023).

However, like many crops, sugarcane production in Pakistan faces significant challenges due to climate change, land degradation, and water scarcity, which impact both yields and sustainability. Between 1999 and 2018, Pakistan was among the countries most affected by extreme weather events, which altered the essential parameters for agricultural viability, including temperature, rainfall, and soil quality (Alvar-Beltrán et al., 2021; Stevenson et al., 2018).

The Intergovernmental Panel on Climate Change u(IPCC) has reported global temperature increases of 0.3°C to 1.7°C, leading to both short-term and long-term climatic events ((Larsen et al., 2011; Mitsch & Hernandez, 2013; Morel et al., 2014).

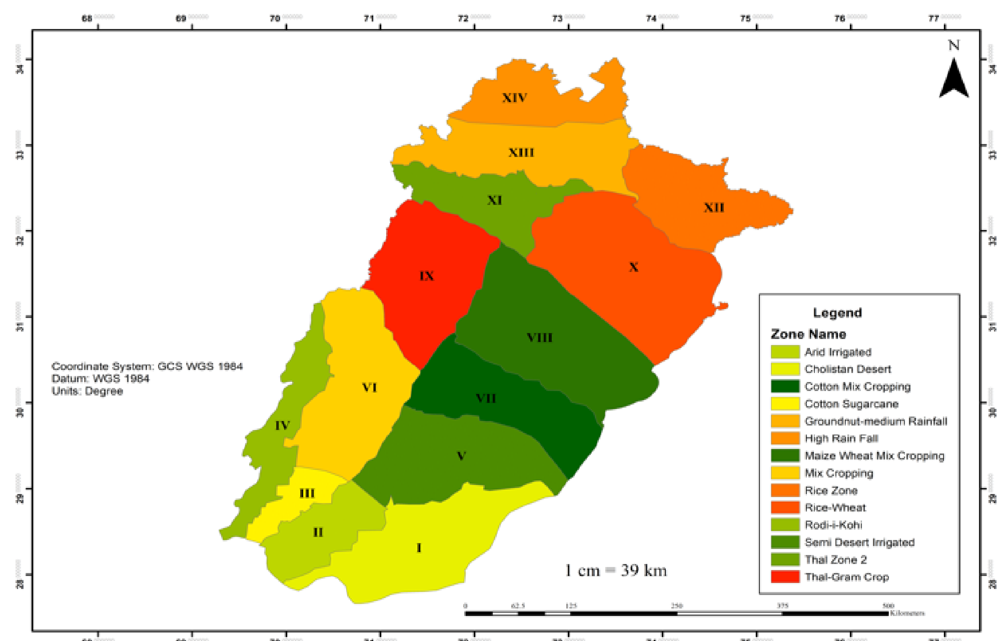

Fig 1: Agro Ecological Zone by FAO-2019 Map shown the 14 new Agro ecological zone which fulfill the requirement of new Agro climate Change. Agro-ecological zones were delineated using the FAO approach, based on climatic and soil characteristics, crop norms, and economic variables. Zone-III represent Cotton Sugarcane Zone

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Addressing these challenges requires updated agricultural management practices and more accurate methods for evaluating land suitability. The Food and Agriculture Organization (FAO) has developed global guidelines for land suitability, which consider factors such as soil type, climate, and topography. However, these models often fail to account for local socio-economic and cultural factors, leading to discrepancies between FAO suitability assessments and local agricultural practices (Khan et al., 2023) (Yasar et al., 2015)

In Punjab, the Pakistan Agriculture Research Council (PARC) established agricultural zones in 1980, but these zones are now outdated due to rapid climate changes (Naheed & Mahmood, 2015). There is an urgent need to redefine these zones to enhance productivity and sustainability. By comparing the FAO-recommended sugarcane cultivation zones with actual local trends, this study aims to identify gaps and propose necessary adaptations for the future.

Due to the influence of Climate change on agriculture, the FAO has introduced new cropping zones for suitable cropping under changing climatic conditions, primarily due to changes in temperature and annual rainfall. FAO new AEZ consists 14-Zones as mentioned in Fig 1. Zone III is nominated as Agro-ecologically suitable area for cotton and sugarcane crop by FAO.

The integration of modern technologies such as Geographic Information Systems (GIS) and Remote Sensing (RS) offers valuable tools to address these challenges. GIS and RS provide spatial data that can monitor crop health, assess environmental conditions, and analyze land nuse patterns (Palaniswami et al., 2011) (Abd-Elmabod et al., 2019). These technologies have already proven effective in identifying suitable lands for sugarcane cultivation, optimizing irrigation, and predicting yields, making them indispensable for sustainable agricultural management. For instance, remote sensing has been used to estimate sugarcane yield with a high degree of accuracy (Bastiaanssen & Ali, 2003).

The primary objectives of this research are twofold. First, to conduct a geospatial comparison between the FAO-recommended suitable areas for sugarcane cultivation and the areas currently cultivated by local farmers. Second, to perform a temporal analysis of crop reporting services in relation to the FAO guidelines, thereby evaluating how sugarcane cultivation patterns in Punjab have evolved in response to various factors, including climate change. By integrating global models with local data, this research aims to provide a more nuanced understanding of agricultural suitability and inform policy and practice for sustainable crop production in Punjab.

2. DATASETS AND SOURCES

The research focuses on Punjab Province, Pakistan's agricultural hub, with a 205,334 km² area characterized by its fertile soil and varied climate. Home to over 110 million people, many of whom are small-scale farmers, Punjab stands as a leading sugarcane producer with an output of approximately 27.6 tons per acre over five years (PBS, 2017).

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The region experiences semi-arid conditions, with rainfall ranging from 960mm in hilly areas to 460mm in the plains. Key crops include wheat, sugarcane, rice, maize, and cotton, alongside a variety of vegetables. Agricultural cycles are split into Kharif (summer) and Rabi (winter) seasons, with respective sowing and harvest times. The area's diverse crop patterns and climatic zones are depicted in Fig 2.

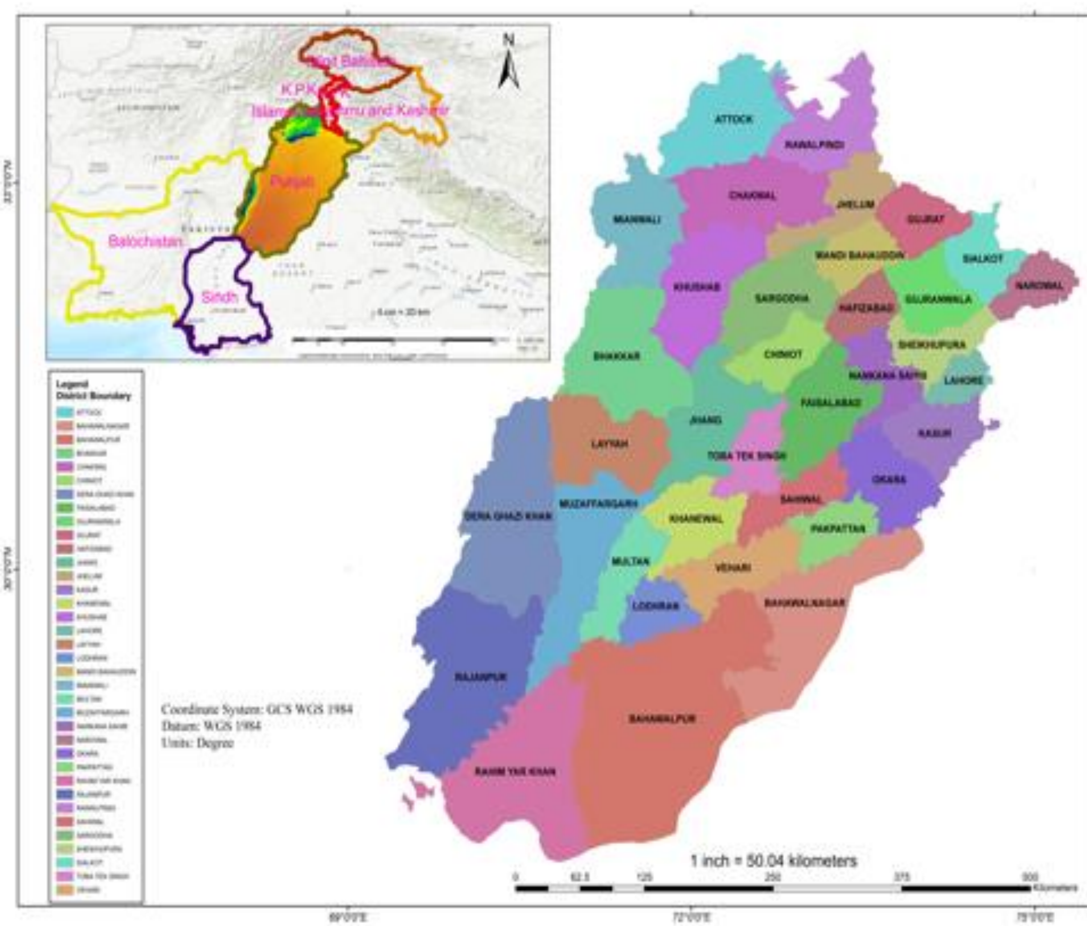

Fig 2: Map showing the Study Area of Punjab Province, Pakistan Punjab Province have 36 Districts

The research utilizes a variety of datasets to analyze sugarcane cultivation. The first dataset consists of a digitized sugarcane crop map obtained from the Food and Agriculture Organization (FAO), which provides detailed vector data on sugarcane distribution.

The second dataset includes comprehensive crop reporting data spanning the last 32 years, sourced from the Agriculture Department of the Government of Punjab; this dataset takes the form of extensive reports detailing crop patterns and yields.

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Lastly, biomass imagery with a 30-meter resolution from the Landsat-8 OLI-TIRS satellite offers raster data, which is crucial for assessing the physical conditions affecting crop growth.

(FAO, 2019) In 2019, the FAO released a detailed Agro-Ecological Zones (AEZ) report, defining regions based on climate and soil factors. A key output was the AEZ map, distinguishing 14 zones through climate data from 2000 to 2017 and extensive soil sampling.

Zone III was identified for optimal cotton and sugarcane cultivation. Complementing this, FAO crafted 59 crop suitability maps, weighing agro-climatic and economic factors to delineate regions fit for sugarcane farming into three classes, detailed in Table 1 and Fig 5. This classification utilized percentile values and an economic equation to gauge viable cultivation areas (FAO, 2019).

Table 1: FAO Economic suitability of Sugarcane Calculated on the basis of Net return (Rs/ha) on each crop calculating at each district by using equation no 1, subtraction of total cost from total revenue(AMIS, 2023) calculated total cost

Sr.#	Classes	Maximum Profit Percentile (%)	Value
1	High Suitable	>66	25993-39383
2	Marginal Suitable	>33 and <66	1326-25992
3	Less Suitable	<33	25992

Additionally, the study gauges sugarcane's practical viability by computing the gross margin against the cost of production, following a formula for net return that balances total revenue with total costs, accounting for both variable and fixed expenses (PITCO & Oy, 2016).For land cover and crop classification, biomass images were crafted using Landsat-8 data employing probability models and field samples to ensure accuracy. These images are pivotal for understanding the agricultural landscape and guiding sugarcane cultivation strategies.

To estimate agricultural yields accurately, the study employs meticulously structured opinion surveys based on village-level samples. For each district, 174 plots are carefully selected, with each covering roughly 15x20 feet. The yield per plot is calculated in kilograms, and the average district yield is determined by dividing the total yield by the surveyed plot count.

The selection process maintains rigor by randomly choosing six plots from each village through a lottery system. For standardization, yields are converted from kilograms to mounds per acre using a factor of 3.89.

This allows for uniform data comparison. The final step in determining total district production involves multiplying the average yield (in mounds per acre) by the district's total acreage. The details of methodology are given in Fig 3.

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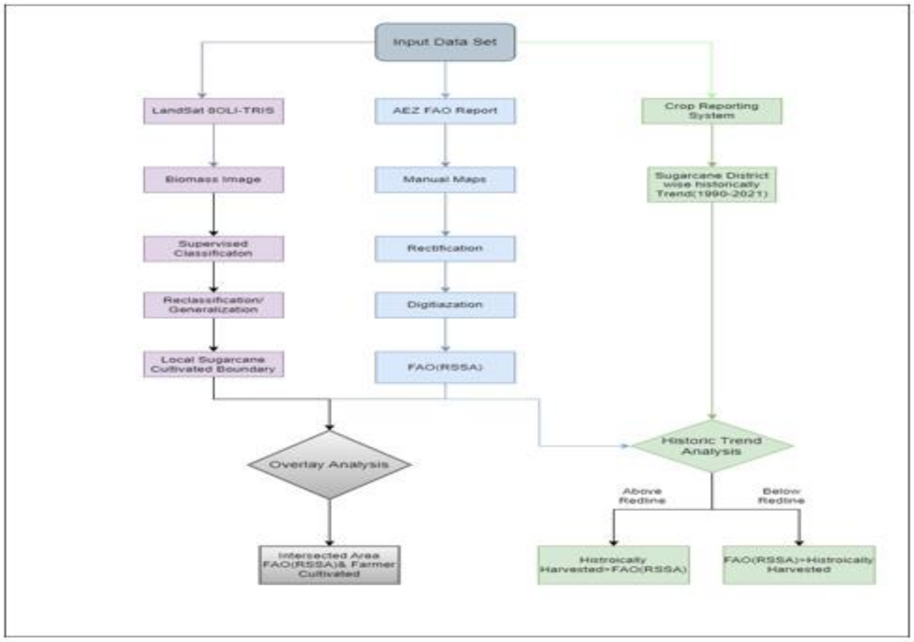

Fig 3: Data Sets & Processes used for sugarcane Cultivation Analysis

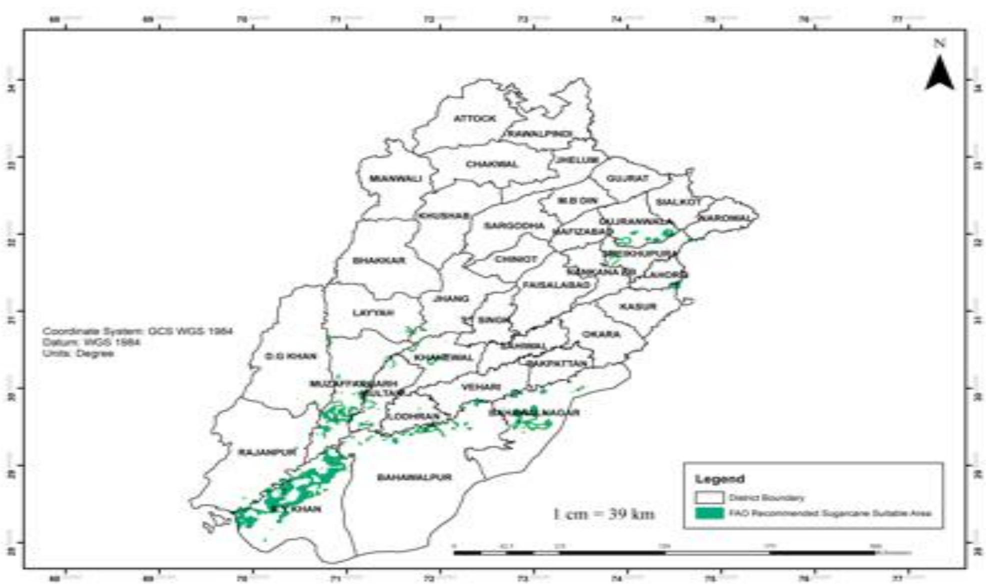

Fig 4: FAO (RSSA) FAO Recommended Sugarcane Suitability Area District wise Map of Punjab Agro-Ecological Zone developed this map on basis of 4 steps 1. Agro-Climatic Zone 2. Agro Ecological Zone 3.Total Available Water 4. Assessment of Land Characteristics

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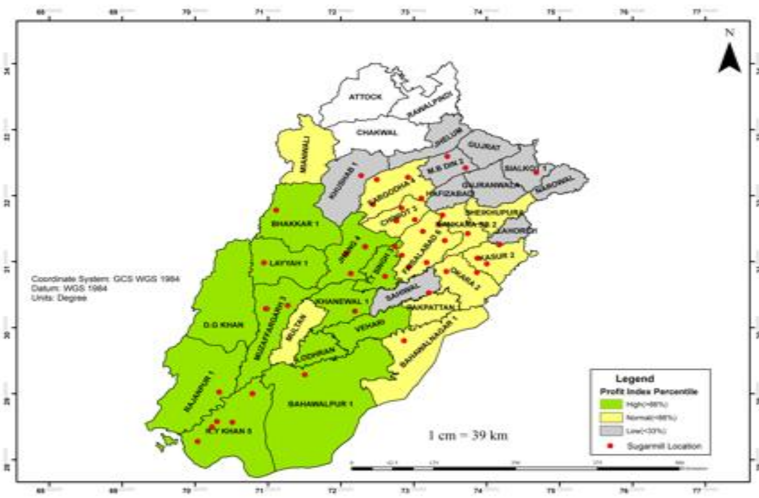

Fig 5: FAO percentile wise profit index map with Factory Mill location. Agro economic assessment showing the Net return calculated by subtracting the total cost from total return. It helps us in calculating that sugarcane crop economically feasible in this district for farmer or not. This maps also shown the number of mills fall in each district

3. METHODOLOGY

3.1 Creation of Suitability and Profitability Index Maps:

The initial phase of the study focused on utilizing the FAO's agro-climatic zone and profit index map as benchmarks. To integrate these benchmarks with various datasets, we first vectorized the FAO map, converting it from its original format into a digital vector format suitable for analysis. The next step involved aligning this vectorized map with other relevant datasets through precise georectification. This process ensured that the FAO map accurately matched geographic coordinates, enabling a comprehensive comparison and analysis of the current sugarcane cultivation scenarios against FAO benchmarks. Fig 4 illustrate the outcomes of this alignment.

3.2 Land Classification using Landsat 8 OLI Tier Data for Sugarcane Area Identification

Following the initial phase, biomass image analysis was employed to validate the areas actually cultivated with sugarcane. This process involved a supervised classification of Landsat-8 OLI-TRIS data, resulting in the identification of 23 distinct classes, as outlined in Table 2. From this dataset, two primary categories were established through reclassification: Sugarcane and Non-Sugarcane. Within the Sugarcane category, five specific biomass data subclasses were identified and detailed in Table 2, while the remaining classes were categorized as Non-Sugarcane, each assigned a value of '0'. Figs 6 illustrate the outcomes of this alignment. The classified data was then converted

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into vector format to enhance the GIS integration of various geographic layers. This conversion is pivotal for conducting sophisticated overlay and proximity analyses, details of which will be explored in the next section of this study. Such analyses are critical for the application of post-classification decision rules that synergistically use all available data sources, in accordance with the guidelines set forth by (Thomas M. Lillesand, 2015). This structured approach ensures a comprehensive and precise analysis of sugarcane cultivation areas.

3.3 Comparison of FAO Designated Suitable Areas with Areas Identified through Classification

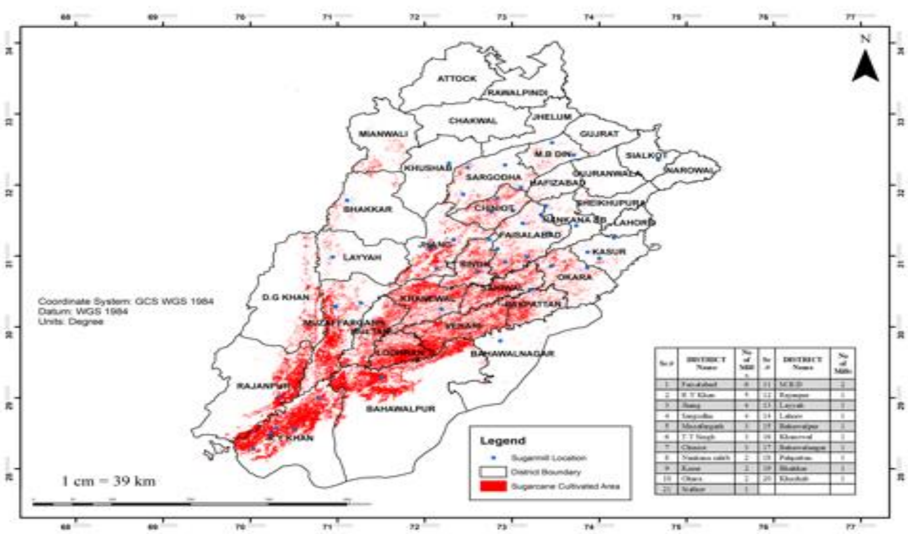

Fig 6: Bio mass image shown the sugarcane cultivated area by farmers

Table 2: Land use 23-classes extracted from Landsat-8 image by using supervised image classification

Sr. No	Class Name	Sr. No	Class Name
1	Cotton-maize	12	Rice-sugarcane
2	Cotton-other crop	13	Rice-wheat
3	Cotton-rice	14	Sugarcane-sugarcane
4	Cotton-sugarcane	15	Sugarcane-wheat
5	Cotton-wheat	16	Wheat-wheat
6	Maize-maize	17	Bare area
7	Maize-rice	18	Low biomass
8	Maize-sugarcane	19	Medium biomass
9	Maize-wheat	20	High biomass
10	Other_crop	21	Road
11	rice-rice	22	Urban
23	Water		

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An overlay analysis is conducted to integrate and compare two crucial datasets: the FAO's Recommended Sustainable Sugarcane Area (RSSA) and the actual biomass image areas representing sugarcane cultivation by farmers within Punjab, Pakistan. This analysis identifies intersected areas, where FAO-sanctioned suitable zones and farmer-cultivated areas overlap, as well as non-intersected areas, where these zones do not align. Fig 7 illustrated the outcome. By comparing the designated suitable areas according to FAO guidelines with the actual cultivated areas detected in biomass images, the analysis provides a detailed view of where current sugarcane cultivation practices align with or deviate from recommended sustainable practices. This approach not only highlights areas of compliance and discrepancy but also helps to assess the effectiveness and practicality of FAO's agricultural zoning. This detailed comparison shown in table 3 serves to illustrate the practical challenges and adaptations made by local farmers, shedding light on potential areas for policy adjustment or targeted support to enhance sugarcane production's sustainability and alignment with international agricultural standards. Through this comprehensive overlay analysis, the research aims to derive valuable insights into the real-world implications of agricultural policy and the adaptive strategies of farmers within these zones.

3.4 Analysis of Historical Trends in Sugarcane Cultivation Areas

To understand the historical adherence of sugarcane cultivation in Punjab province to FAO recommendations, a historical trend analysis covering a 32-year period from 1990 to 2021 was conducted. This method, a form of time series analysis, examines patterns and trends in the historical data to forecast future tendencies, appraise past agricultural performance, and facilitate informed future decision-making. The trend analysis examined the degree to which historical sugarcane cultivation patterns in the region conformed to the FAO's RSSA guidelines. The data for this analysis was sourced directly from the farmers, providing a robust primary source that offers insight into agricultural practices, systematically documented in Form 6-A. An extensive compilation of data spanning three decades of sugarcane cultivation across various districts, accounting for thousands of acres, was analyzed. This dataset formed the basis for comparison against the FAO's RSSA benchmarks. The analysis used the following formula to establish a baseline for comparison:

Equation 1 FAO Recommended Sugarcane Suitable Area

$$\Delta A = A_{RSSA} - A_{sc-hist} \qquad (1)$$

WhereΔA is the value representing the deviation from FAO (RSSA) guideline,

A_{RSSA} is the area recommended by the FAO’s RSSA for sugarcane cultivation, and

$A_{sc-hist}$ is the actual area cultivated with sugarcane from 1990 to 2021, Establishing this baseline is essential for a deepened understanding of the agricultural practices across districts and the evolution of sugarcane farming relative to sustainability standards. This alignment, or lack thereof, provides valuable insights into the practical

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application of FAO guidelines and the adaptability of local farming practices over the years.

4. RESULTS

4.1 Overlay analysis for Comparison of biomass area with FAO (RSSA)

An in-depth overlay analysis was conducted to compare the areas of sugarcane cultivation as reported by farmers with those designated by the FAO's Recommended Sustainable Sugarcane Area (RSSA). This comparison, depicted in Figs 8 through 11 and summarized in Table 3, meticulously highlights both the areas where FAO recommendations are followed (intersected areas) and where they are not (non-intersected areas). According to the analysis, the FAO (RSSA) has recognized 18 districts as suitable for sugarcane cultivation, covering a vast expanse of 1,745,713 acres. However, it was discovered that only 58,570 acres, or 3.3% of this recommended land, actually adhere to these guidelines, spanning 33 districts. Notably, a significant portion of sugarcane cultivation occurs in 15 additional districts that the FAO (RSSA) has not marked as suitable, illustrating a considerable deviation from recommended practices. Figs 8 and 10 specifically highlight Southern Punjab as the region most aligned with FAO's suitability assessments for sugarcane cultivation.

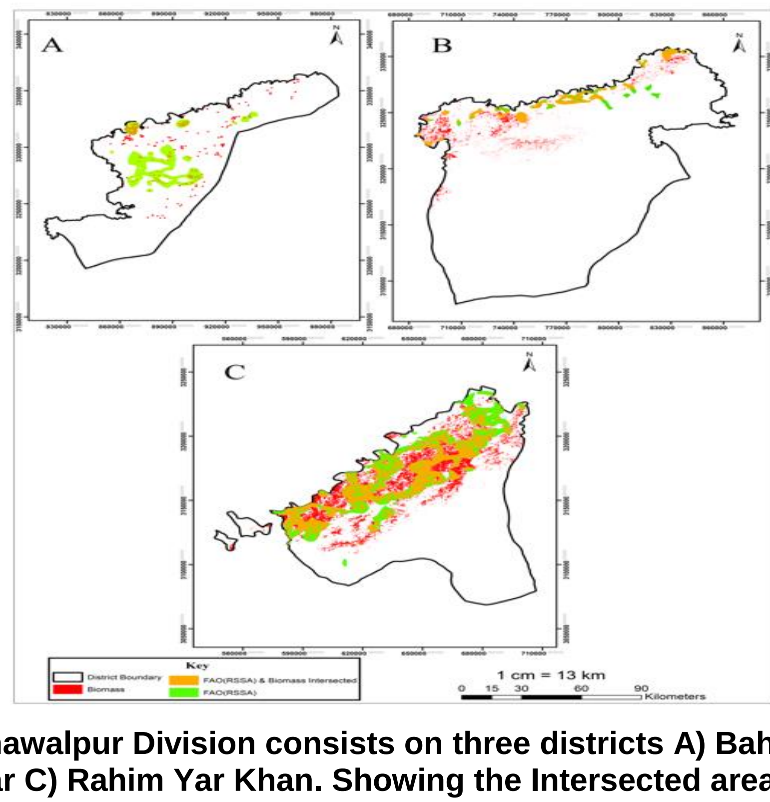

Fig 7: Bahawalpur Division consists on three districts A) Bahawalpur B) Bahawalnagar C) Rahim Yar Khan. Showing the Intersected area between FAO (RSSA) & Biomass. Intersected area where our farmer follow the FAO (RSSA.) Also shown the biomass & FAO (RSSA) area which does not overlay

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Furthermore, the FAO has developed a profit index for the sugarcane crop, presented in Fig 4 and Table 3. Intriguingly, among the 18 districts deemed most suitable by the FAO (RSSA), only 10 achieved a high profit index rating. The remaining districts were categorized into normal or low profit index classes.

This disparity in profitability underscores the complex interplay between geographical suitability, agricultural practices, and economic outcomes. This comprehensive analysis not only confirms the alignment and discrepancies between the FAO's zoning and actual farming practices but also sheds light on broader implications for agricultural policy and local farming strategies.

The detailed mapping and comparative assessment serve to inform potential policy adjustments and targeted support, aiming to enhance the sustainability of sugarcane production and ensure it aligns with international agricultural standards.

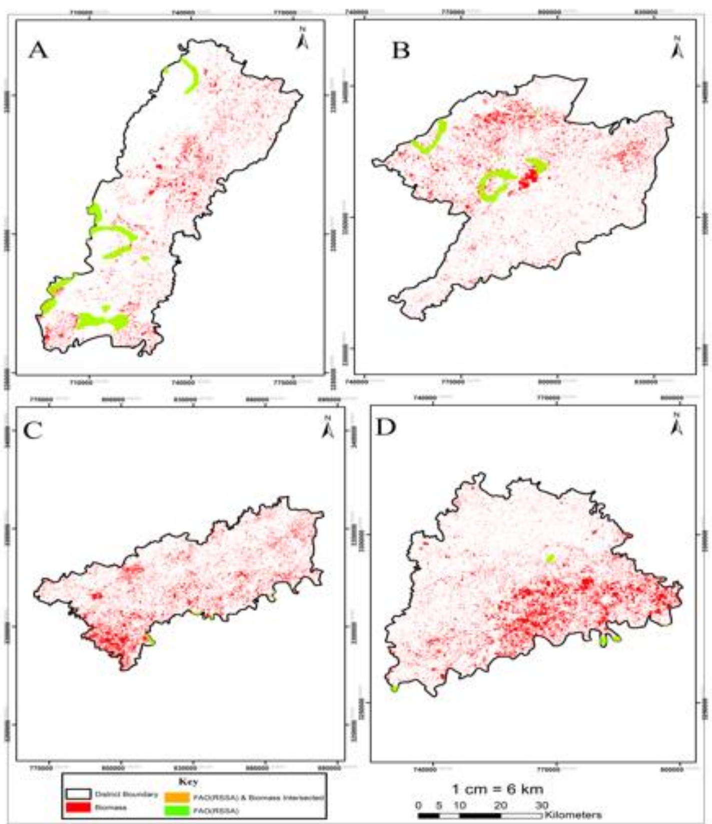

Fig 8: Multan Division consists on four districts A, Multan B) Khanewal C, Vehari D) Lodhran. Showing the Intersected area between FAO (RSSA) & Biomass. Intersected area where our farmer follow the FAO (RSSA.) Also shown the biomass & FAO (RSSA) area which does not overlay

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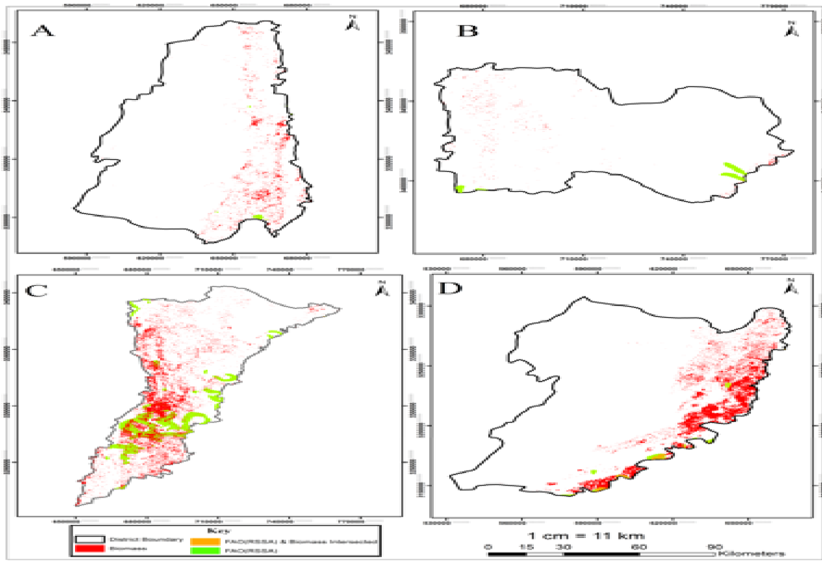

Fig 9: D.G Khan Division consists on four districts A) D.G Khan B) Layyah C) Muzafargarh D) Rajanpur. Showing the Intersected area between FAO (RSSA) & Biomass. Intersected area where our farmer follow the FAO (RSSA.) Also shown the biomass & FAO (RSSA) area which does not overlay

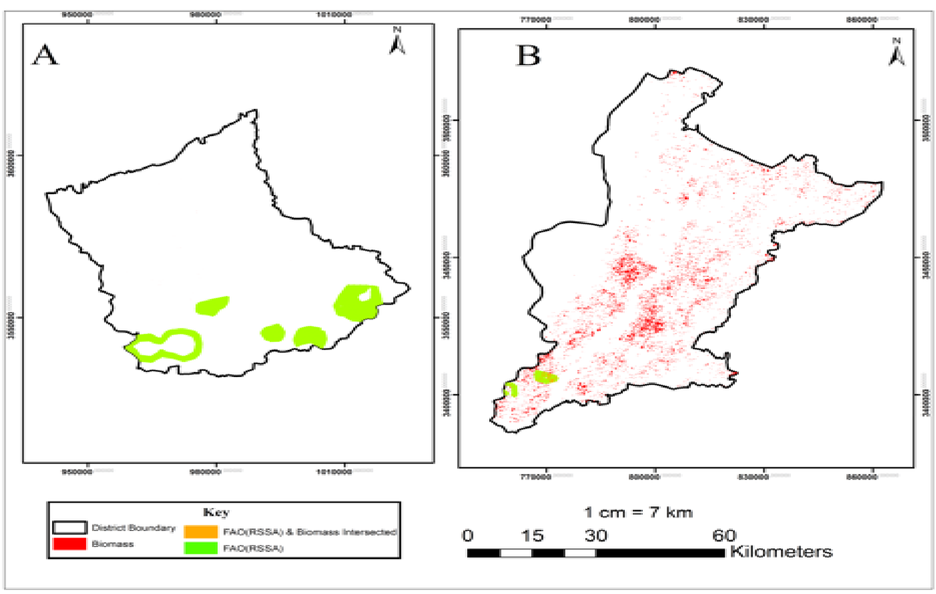

Fig 10: Two districts A, Gujranwala B)Jhang. Showing the Intersected area between FAO(RSSA) & Biomass. Intersected area where our farmer follow the FAO(RSSA.) Also shown the biomass & FAO(RSSA) area which does not overlay

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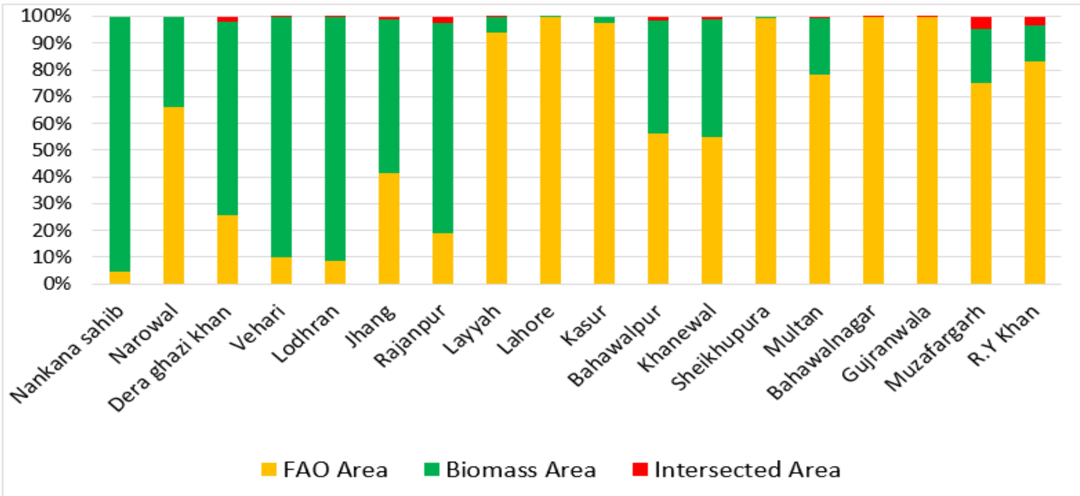

Fig 11: Graphical presentation District Wise Comparison FAO(RSSA) & Biomass Intersected Area in this graph. 18 District selected by FAO(RSSA) out of 36 districts. Green line shows where according FAO(RSSA) Intersected Area shown that farmer followed the FAO(RSSA) as per describe by AEZ-2019

Table 3: FAO(RSSA) & Sugarcane grown area (Biomass) image for Sugarcane crop comparison with Profit index and existing Sugarcane processing mills district wise

Sr	District Name	FAO Area (Acers)	Biomass Area (Acers)	FAO & Biomass both recommended Intersected Area (Acers)	FAO Not Recommended but Biomass-exist(Acers)	FAO Recommended but not Biomass Exist(Acers)
1	Nankana sahib	12	249	0	249	12
2	Narowal	37	19	0	19	37
3	Dera ghazi khan	4478	12722	325	12397	4153
4	Vehari	5071	44917	170	44747	4901
5	Lodhran	3511	37537	9	37528	3502
6	Jhang	11187	15505	335	15170	10852
7	Rajanpur	27454	113480	3830	109650	23624
8	Layyah	14512	872	43	829	14469
9	Lahore	5102	2	0	2	5102
10	Kasur	14273	381	0	381	14273
11	Bahawalpur	157385	118058	4286	113772	153099
12	Khanewal	37991	30669	744	29925	37247
13	Sheikhupura	30778	140	0	140	30778
14	Multan	60553	16328	402	15926	60151
15	Bahawalnagar	210506	337	127	210	210379
16	Gujranwala	89372	8	2	6	89370
17	Muzafargarh	234875	62612	15263	47349	219612
18	R.Y Khan	838615	133770	33033	100737	805582
	* Area in acers	1745712	587606	58569	529037	1687143

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4.2 Historic Trend Analysis with FAO(RSSA)

Further the research presents the findings of the historical trend analysis of sugarcane cultivation in Punjab, with a detailed breakdown provided in Table 4. The trend outcomes are visually represented in Fig 12, where a red line establishes the baseline for FAO's recommended cultivation levels. The analysis reveals varied adherence across the regions: eight districts are depicted above the red line, indicating that these areas have consistently cultivated more sugarcane than recommended by the FAO. This suggests a trend of overproduction relative to FAO guidelines, potentially driven by favorable local conditions or market demands.

Conversely, seven districts are shown below the red line, where sugarcane cultivation is less than what is recommended. This underproduction may reflect local constraints such as suboptimal farming conditions or economic factors that discourage adherence to FAO recommendations. Additionally, three districts exhibit variable compliance, aligning with the FAO's recommendations in some years while deviating in others. This fluctuating adherence could be influenced by changes in local policies, economic incentives, or environmental factors that affect agricultural practices.

While the graphic representation includes all 36 districts studied, the primary focus of this analysis centers on the 18 districts explicitly recommended by the FAO for sugarcane cultivation. The remaining districts, not endorsed by the FAO for these crops, are noted above the red line, underscoring a broader regional analysis of cultivation practices against sustainable agricultural standards set forth by the FAO.

This detailed examination not only highlights the discrepancies and adherence levels across different districts but also sheds light on the complexities of agricultural management in relation to FAO guidelines. The insights gained from this analysis could inform targeted policy interventions aimed at enhancing the sustainability and economic viability of sugarcane production in Punjab.

Table 4: FAO recommended districts Historic Trend Analysis table trend status “Above” mean Historically not follow FAO(RSSA) & “Below” mean Historically follow FAO(RSSA)

Sr	District	Trend Status Redline	Sr	District	Trend Status Redline
1	JHANG	Above	10	R.Y KHAN	Below
2	D. G KHAN	Above	11	MUZAFARGARH	Below
3	VEHARI	Above	12	BAHAWALPUR	Below
4	LAYYAH	Above	13	KHANEWAL	Below
5	LODHRAN	Above	14	MULTAN	Below
6	KASUR	Above	15	BAHAWALNAGAR	Below
7	NANKANA SIB	Above	16	GUJRANWALA	Below
8	NAROWAL	Above	17	LAHORE	Both
9	RAJANPUR	Both	18	SHEIKHUPURA	Both

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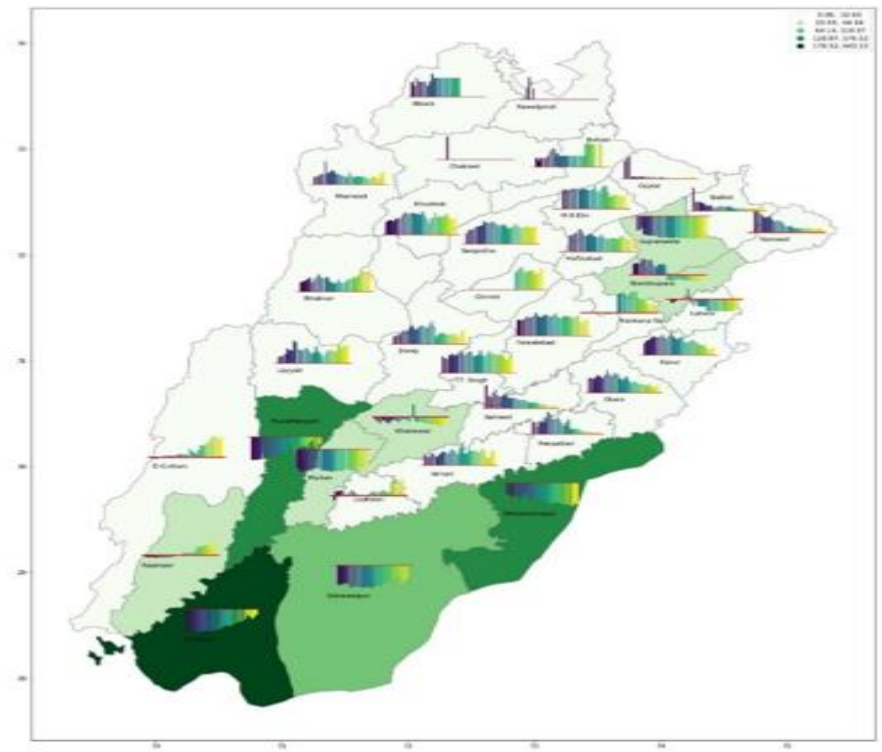

Fig 12: Graphical 32-years (1990-2021) historic trend analysis CRS with FAO(RSSA) Graph height shows the cultivated area increases, decrease in past 32-Years data. Above redline cultivated area more than recommended area, below redline means recommended area more than cultivated area

5. DISCUSSION

The research employs an integrated approach combining remote sensing and geographical information systems to enhance the production management of sugarcane crops across Punjab. This approach builds on previous studies such as those by (Khurshid et al., 2020) which evaluated the performance of sugarcane clones and the impacts of climatic changes on crop yield under the specific agro-climatic conditions of Faisalabad.

The crop encounters several obstacles such as below-average production per unit area, limited sugar recovery, and increased production costs. Additionally, the prevalent practice of planting in traditional zones unsuitable for cultivation, rather than adopting the new Agro-ecological zones defined by the FAO, is the primary reason for reduced cane and sugar yields. Unsuitable locations are identified as the primary factor contributing to both the increase and decrease in cane yield per unit area (Mian, 2006). Similarly, this study aims to leverage new technologies to gain accurate insights into the sugarcane cultivation patterns in Pakistan, particularly how these patterns align with FAO recommendations.

ISSN: 1673-064X
E-Publication: Online Open Access
Vol: 67 Issue 10 | 2024
DOI: 10.5281/zenodo.14058667

The overlay and historical trend analyses conducted shown in Figs 11&12 in this study provide a deep dive into the cultivation patterns across the Punjab province. The FAO's Recommended Sustainable Sugarcane Area (RSSA) identified 18 districts as optimal for sugarcane cultivation. Notably, central and southern Punjab, which include districts like Bahawalpur, Bahawalnagar, Rahim Yar Khan, Lodhran, Muzaffargarh, and Rajanpur, have been highlighted as particularly suitable due to their humid climate conditions conducive to sugarcane production. This region, characterized by ample water supply and fertile soils, forms a sugarcane mix zone ideally positioned for high-yield cultivation.

However, discrepancies in cultivation practices were evident, as shown in Table 3. Fig 5 shows that Nankana Sahib and Narowal, for instance, fell under the "Normal" profit index category yet exhibited more sugarcane cultivation than expected, which could reflect local economic dynamics or mismatches between theoretical suitability and practical viability. In contrast, districts like Gujranwala and Lahore, recommended by FAO, displayed a low profit index, possibly due to local preferences for non-agricultural occupations. Surprisingly, Bhakkar, though declared unsuitable by FAO, fell into a high profit index category, likely due to sugarcane being supplied to its mills from neighboring provinces, suggesting a regional interdependency that impacts local cultivation decisions. The historic trend analysis, encapsulated in Table 4 and visualized through Fig 12, further underscores these findings. It shows that while some FAO-recommended districts such as R.Y Khan and Muzaffargarh are underutilizing their land's potential, others like Jhang and D.G Khan are over cultivating beyond the FAO's suggested limits. This over cultivation could be driven by market demands, economic incentives, or entrenched historical agricultural practices. Moreover, the variable compliance in districts like Lahore, Sheikhupura, and Rajanpur, which oscillate between adhering to and deviating from FAO recommendations, indicates the complex interplay of factors such as seasonal variations, climatic conditions, and market dynamics that influence cultivation decisions. This complexity highlights the need for policies that not only promote sustainable practices but also consider the economic realities and local conditions that influence agricultural decisions.

6. CONCLUSION

In conclusion, Policymakers can leverage the updated Agro-Ecological Zones (AEZs) and related data on land characteristics—such as soil quality, topography, climate, agricultural land use, yield, and profitability—to develop optimal policies for sustainable agricultural production. By further assessing these land characteristics for their production potential, they can make final recommendations on what crops should be cultivated, where they should be planted, and the best methods for their cultivation.

This study significantly underscores the crucial role of integrating remote sensing and GIS technologies to enhance the understanding of sugarcane cultivation dynamics in Punjab. The selection of FAO(RSSA) in terms of higher cane production along with higher sugar recovery might play vital role in prosperity of farmers as well as industrialists. This study

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provides enough information regarding the response sugarcane under agro-ecological conditions of Punjab. The research has illuminated substantial discrepancies between the FAO's Recommended Sustainable Sugarcane Area (RSSA) guidelines and the actual cultivation practices observed across various districts. These discrepancies reveal a complex interplay of factors influencing the farmers' decisions, which often lead to significant deviations from prescribed agricultural guidelines.

The findings highlight areas where sugarcane cultivation exceeds or does not meet the FAO's sustainability criteria, indicating a misalignment between agricultural policies and on-ground practices. Particularly in regions like Southern Punjab, where favorable climatic conditions exist, the alignment with FAO's RSSA is more pronounced, yet significant areas still diverge from these guidelines. This suggests that while environmental conditions are conducive, other factors may influence cultivation practices, leading to the observed discrepancies.

This study advocates for a deeper investigation into the reasons behind such deviations. Understanding why farmers choose to cultivate sugarcane in non-recommended areas or fail to maximize the potential of recommended zones is crucial for developing effective strategies to promote sustainable agriculture. Future research should focus on qualitative analyses that explore the local knowledge, perceptions, and challenges faced by farmers, which may affect their adherence to FAO guidelines.

Additionally, there is a need for ongoing monitoring and evaluation of sugarcane cultivation practices using the advanced tools and methodologies employed in this study. Such efforts can help track the progress of implementing FAO recommendations and identify successful interventions or practices that could be scaled or adapted to similar agricultural contexts.

Ultimately, the goal is to bridge the gap between policy intentions and the realities of agricultural practice. By aligning FAO recommendations more closely with the actual conditions and needs of the farming communities, it is possible to enhance the sustainability of sugarcane cultivation in Punjab, setting a precedent for other regions to follow.

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ISSN: 1673-064X
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