Article

Soybean (*Glycine max*) Cropland Suitability Analysis in Subtropical Desert Climate through GIS-Based Multicriteria Analysis and Sentinel-2 Multispectral Imaging

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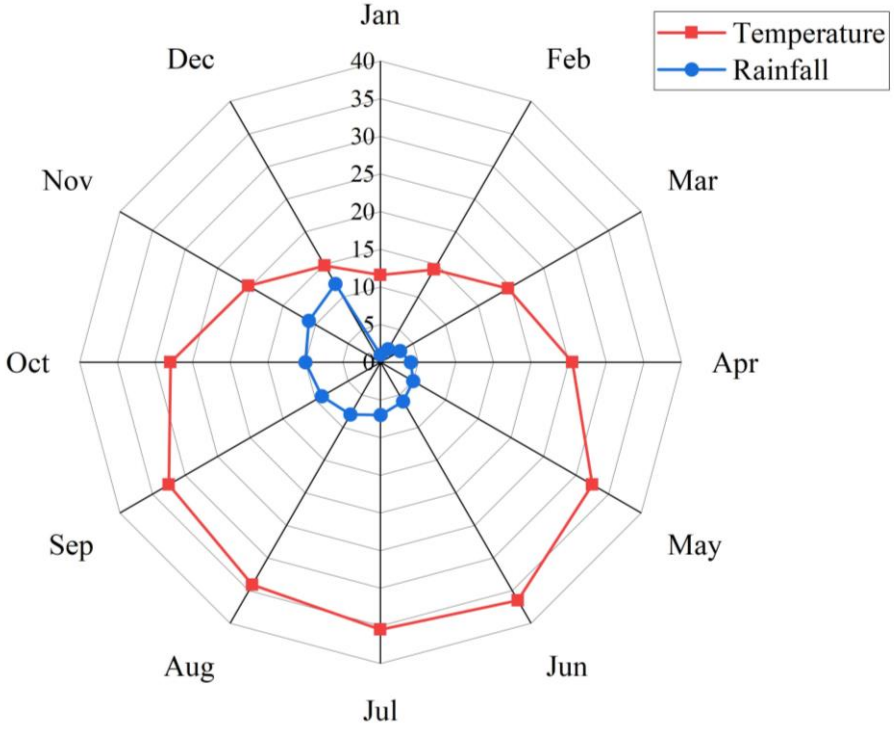

Figure S1. Monthly average met data for the study area, year 2022.

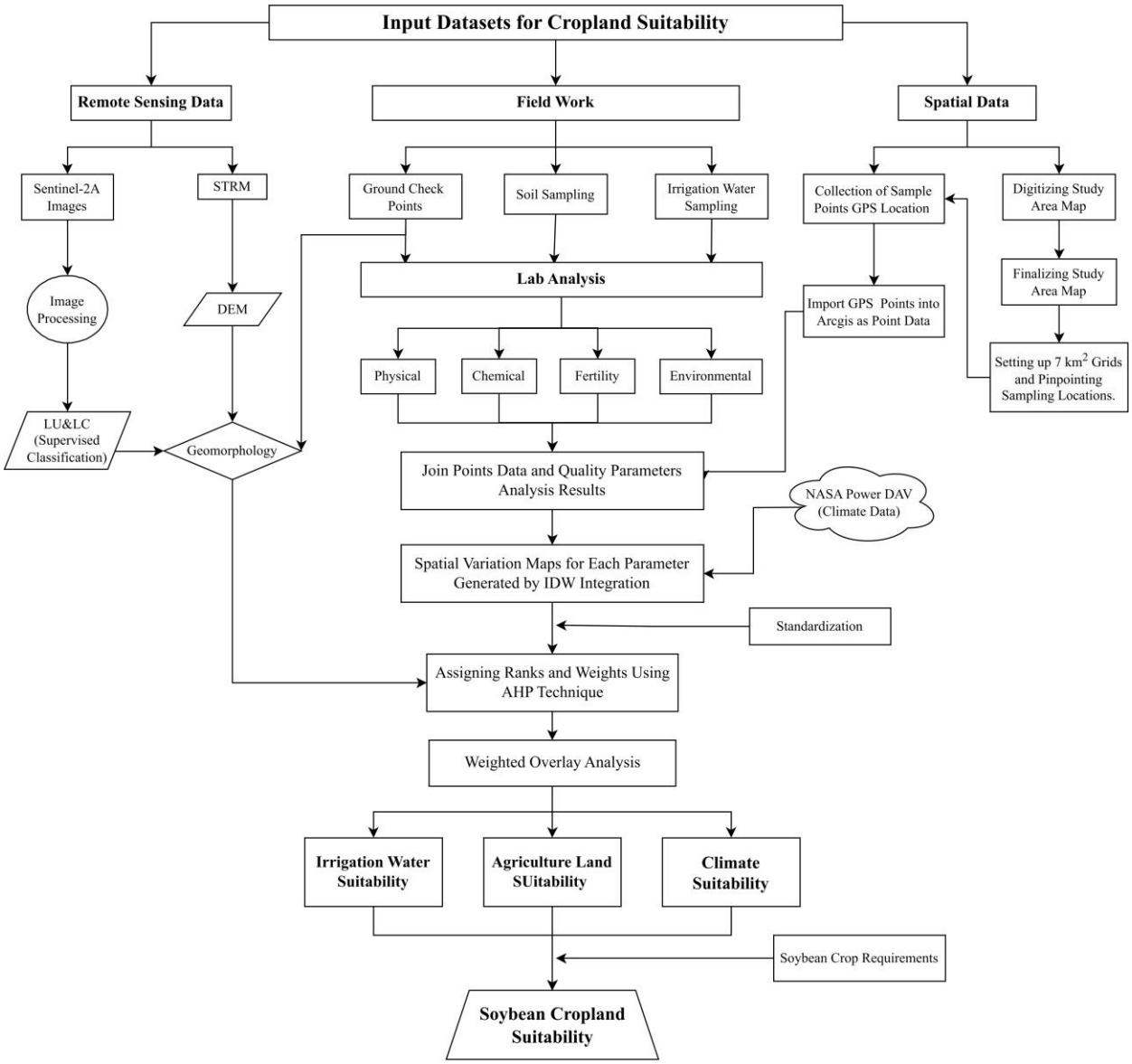

Figure S2. A Visual Overview of the Cropland Suitability Assessment Process.

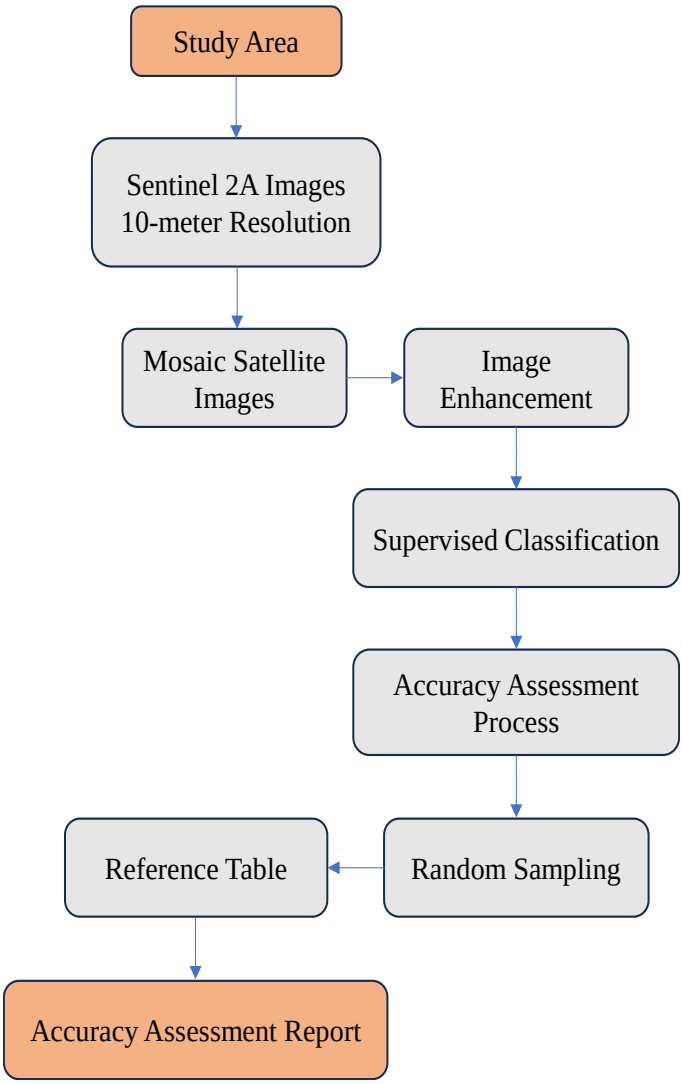

Figure S3. Schematic of workflow for LU&LC *classification* and accuracy assessment.

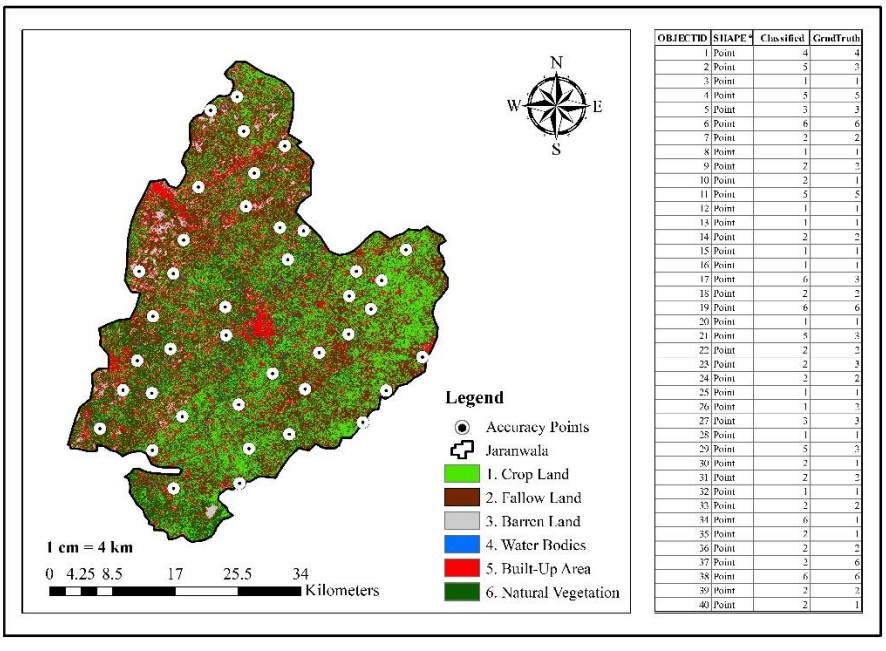

Figure S4. Sentinel 2A (classified) image of the study area, adorned with 40 randomly sampled points.

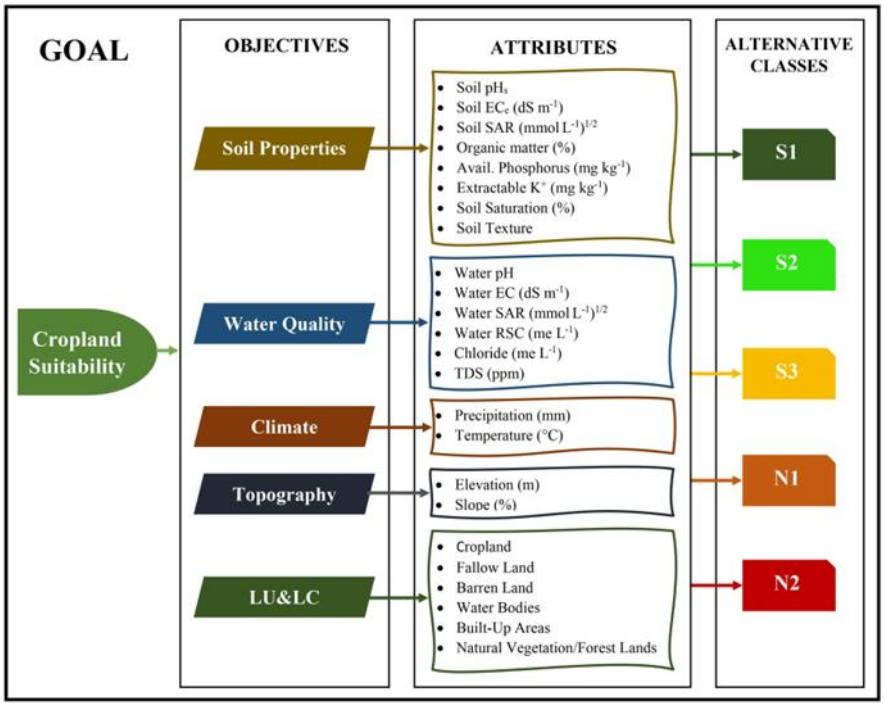

Figure S5. Hierarchical arrangement of assessment standards used in the study.

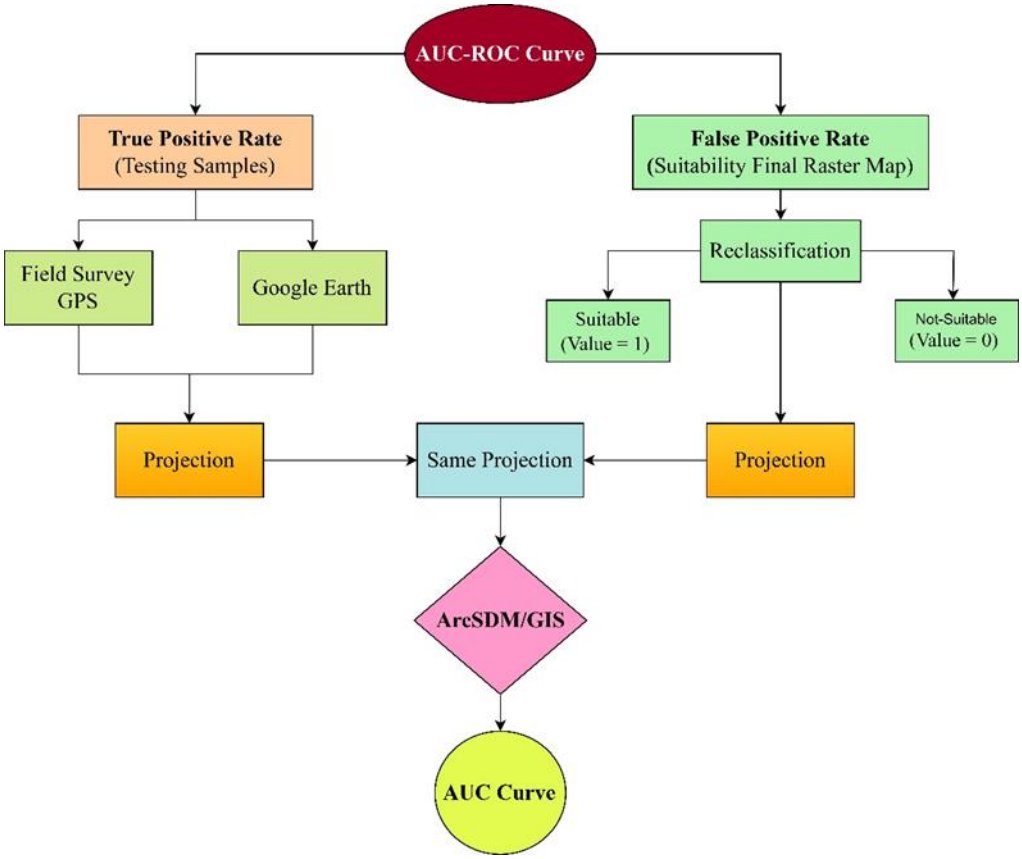

Figure S6. Schematic diagram depicting the receiver operating characteristic (ROC) analysis methodology.

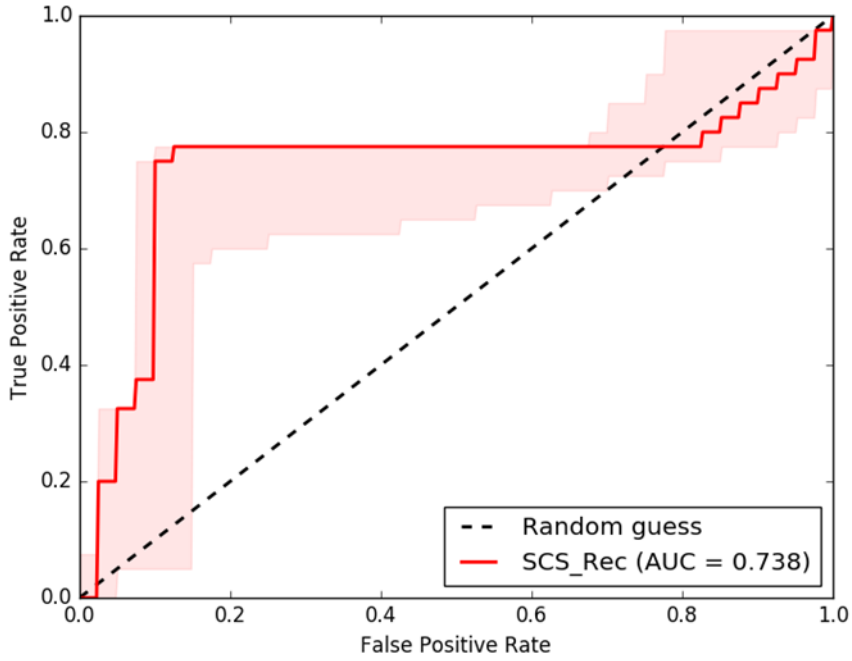

Figure S7. ROC-AUC validation results for Soybean Cropland Suitability (SCS).

Table S1. Spatial location of soil and irrigation water sampling sites.

Sample#	Address Code	X-Coordinates	Y-Coordinates	Water Source	Address
01	648 GB.T	73.48609924	31.33919907	Tube Well	Acre No. 25, Square No. 56, Chak No. 648 G.B, Lahore Road, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
02	647 GB.T	73.56790161	31.29369926	Tube Well	Acre No. 19, Square No. 15, Chak No. 647 G.B (Kot Bala karam), Lahore Road, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
03	569 GB.T	73.56590271	31.33359909	Tube Well	Acre No. 7, Square No.7, Chak No. 569 G.B (Abdullah Khan), Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
04	643 GB.T	73.62229919	31.35050011	Tube Well	Acre No. 1, Square No. 5, Chak No. 643 G.B (Sattarnagar), Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
05	235 GB.C	73.48809814	31.39920044	Canal Water	Acre No. 18, Square No. 15, Chak No. 235 G.B, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
06	563 GB.T	73.6207962	31.41130066	Tube Well	Acre No. 15, Square No. 57, Chak No. 563 G.B (Baggi Mahal), Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
07	59 GB.T	73.43190002	31.41600037	Tube Well	Acre No. 15, Square No. 41, Chak No. 59 GB (Atalgarh), Shah Kot Road, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
08	635 GB.C	73.54799652	31.40979958	Canal Water	Acre No. 03, Square No. 50, Chak No. 635 GB (Kot Sardaran), Nankana Sahib Road, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
09	99 RB.C	73.36779785	31.47480011	Canal Water	Acre No. 09, Square No. 17, Chak No. 99 RB (Jandiala Kalan), Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
10	95 RB.C	73.43599701	31.47459984	Canal Water	Acre No. 18, Square No. 23, Chak No. 95 (New Jamsher), Dosanj to New Jamsher Road, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
11	90 RB.T	73.43039703	31.54850006	Tube Well	Acre No. 23, Square No. 31, Chak No. 90 RB (Chitti Khurd), Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
12	52 RB.T	73.42359924	31.61070061	Tube Well	Acre No. 06, Square No. 72, Chak No. 52 RB (Bawa Chak), Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
13	68 RB.C	73.36699677	31.54089928	Canal Water	Acre No. 21, Square No. 16, Chak No. 68 RB (Kallah), Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
14	77 RB.C	73.30280304	31.48380089	Canal Water	Acre No. 19, Square No. 38, Chak No. 77 RB (Lohka Kalaan), Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
15	103 GB.T	73.36640167	31.41049957	Tube Well	Acre No. 05, Square No. 16, Chak No. 103 GB (Pathanwala), Khurianwala Road, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
16	61 GB.T	73.4334238	31.3723466	Tube Well	Acre No. 02, Square No. 03, Chak No. 61 GB (Nai Abadi), Khurianwala Road, Tehsil Jaranwala, District Faisalabad, Province

					Punjab, Pakistan
17	2 GB.T	73.50039673	31.29170036	Tube Well	Acre No. 16, Square No. 12, Chak No. 651/2 GB (Ghos Nagar), Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
18	274 GB.T	73.36720276	31.16539955	Tube Well	Acre No. 04, Square No. 19, Chak No. 274 GB (Bacheana), Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
19	633 GB.T	73.49539948	31.22570038	Tube Well	Acre No. 20, Square No. 36, Chak No. 633 GB (Jhok Bhukari), Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
20	89 GB.C	73.17960358	31.22060013	Canal Water	Acre No. 08, Square No. 35, Chak No. 89 GB, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
21	229 GB.C	73.24569702	31.14850044	Canal Water	Acre No. 17, Square No. 08, Chak No. 229 GB (Fazalpura), Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
22	34 GB.C	73.24130249	31.28389931	Canal Water	Acre No. 06, Square No. 10, Chak No. 34 GB (Boote di chal), Satiana Road, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
23	116 GB.T	73.23439789	31.22170067	Tube Well	Acre No. 07, Square No. 12, Chak No. 116 GB, Satiana Road, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
24	24 GB.C	73.31369781	31.27499962	Canal Water	Acre No. 18, Square No. 11, Chak No. 24 GB (Gangapur), Satiana Road, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
25	353 GB.C	73.43890381	31.28540039	Canal Water	Acre No. 13, Square No. 21, Chak No. 353 GB (Kot Baqar), Sayedwala Road, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
26	384 GB.T	73.36640167	31.2227993	Tube Well	Acre No. 09, Square No. 02, Chak No. 384 GB (Chaku), Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
27	CM.T	73.42829895	31.1753006	Tube Well	Acre No. 14, Square No. 01, Chah Mughlanwala, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
28	378 GB.T	73.41770172	31.2343998	Tube Well	Acre No. 09, Square No. 20, Chak No. 378 GB (Hamand ka Chak), Sayedwala Road, Near Jaranwala Interchange, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
29	277 GB.T	73.30899811	31.17210007	Tube Well	Acre No. 02, Square No. 14, Chak No. 277 GB (Nai Wala), Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
30	112 GB.T	73.37000275	31.3397007	Tube Well	Acre No. 10, Square No. 03, Chak No. 112 GB (Sikandarpur), Faisalabad Road, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
31	113 GB.T	73.25090027	31.34989929	Tube Well	Acre No. 17, Square No. 08, Chak No. 113 GB, Faisalabad Road, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
32	221 RB.C	73.24790192	31.41860008	Canal Water	Acre No. 23, Square No. 05, Chak No. 221 RB (Mulawaran Wala), Faisalabad Road, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
33	65 GB.T	73.3010025	31.34560013	Tube Well	Acre No. 01, Square No. 15, Chak No. 65 GB (Mukanpur), Faisalabad Road, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
34	105 GB.C	73.30699921	31.41200066	Canal Water	Acre No. 22, Square No.6, Chak No. 105 GB (Bangy), Faisalabad Road, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
35	282 GB.T	73.30819702	31.22640038	Tube Well	Acre No. 18, Square No. 09, Chak No. 282 GB (Shahamand), Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
36	21 GB.C	73.37110138	31.29470062	Canal Water	Acre No. 05, Square No. 07, Chak No. 21 GB, Satiana Road, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
37	RP.T	73.61430359	31.29570007	Tube Well	Acre No. 03, Square No. 15, Rangpura, Lahore Road, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
38	DS.T	73.54250336	31.2241993	Tube Well	Acre No. 16, Square No. 02, Dhup Sari, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
39	365 GB.T	73.31520081	31.10759926	Tube Well	Acre No. 13, Square No. 19, Chak No. 365 GB, Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan
40	63 RB.C	73.37039948	31.59320068	Canal Water	Acre No. 10, Square No. 05, Chak No. 63 RB (Nihaloana Sahmal), Tehsil Jaranwala, District Faisalabad, Province Punjab, Pakistan

Table S2. Theoretical confusion matrix for Land Use and Land Cover (LU&LC) classification.

S. No.	Classified	Crop Land	Fallow Land	Barren Land	Water Bodies	Built-Up Area	Natural Vegetation	Total (User)	Correct Sampled
1	Crop Land	10.00	1.00	0.00	0.00	0.00	0.00	11.00	10.00
2	Fallow Land	4.00	10.00	1.00	0.00	0.00	1.00	16.00	10.00
3	Barren Land	0.00	0.00	2.00	0.00	0.00	0.00	2.00	2.00
4	Water Bodies	0.00	0.00	0.00	1.00	0.00	0.00	1.00	1.00

5	Built-Up Area	0.00	0.00	3.00	0.00	2.00	0.00	5.00	2.00
6	Natural Vegetation	1.00	0.00	1.00	0.00	0.00	3.00	5.00	5.00
	Total (Producer)	**15.00**	**11.00**	**7.00**	**1.00**	**2.00**	**4.00**	**40.00**	**30.00**

Table S3. Statistical Parameters for Categorized Accuracy Evaluation.

Classified Data	**Parameters**					
	Omission Error	**Commission Error**	**User Accuracy**	**Producer Accuracy**	**Kappa Coefficient (K)**	**Overall Accuracy (OA)**
Crop Land	33.33	9.09	0.91	0.67	0.00	0.00
Fallow Land	90.91	37.50	0.63	0.91	0.00	0.00
Barren Land	100.00	0.00	1.00	0.29	0.00	0.00
Water Bodies	100.00	100.00	1.00	1.00	0.00	0.00
Built-Up Area	100.00	60.00	0.40	1.00	0.00	0.00
Natural Vegetation	100.00	40.00	0.60	0.75	0.00	0.00
Kappa Coefficient (K)	0.00	0.00	0.00	0.00	**0.61**	0.00
Overall Accuracy (OA)	0.00	0.00	0.00	0.00	0.00	**0.70**

Table S4. Rating criteria of Cohen's Kappa statistics.

S. No.	**Cohen's Kappa Statistics**	**Degree of Consensus**	**Explanation**
1	$K < 0.0$	Poor agreement	The agreement indicates a serious performance issue in the classification model.
2	$0.01 \leq K < 0.20$	Slight agreement	The level of agreement may not be practical for real-world use.
3	$0.21 \leq K < 0.40$	Fair agreement	It indicates moderate alignment between the model's predictions and the true labels.
4	$0.41 \leq K < 0.60$	Moderate agreement	The model's predictions and the true labels exhibit a reasonably good level of concordance.
5	$0.61 \leq K < 0.80$	Substantial agreement	The model's performance is quite robust and practical for real-world use.
6	$K \geq 0.81$	Almost perfect agreement	This strongly indicates the model's accuracy and reliability.

Table S5. Saaty's Analytical Hierarchy Process (AHP) for Irrigation Water.

Matrix		**pH**	**EC**	**SAR**	**RSC**	**TDS**	**Cl^-**	**Normalized Principal Eigenvector**	**+/-**
	#	1	2	3	4	5	6		
pH	1	1	2	3	3	4	4	34.55%	9.9%
EC	2	1/2	1	2	3	3	4	24.35%	7.7%
SAR	3	1/3	1/2	1	2	2	3	15.06%	5.1%
RSC	4	1/3	1/3	1/2	1	3	4	13.18%	6.2%
TDS	5	1/4	1/3	1/2	1/3	1	3	8.05%	3.1%
Cl^-	6	1/4	1/4	1/3	1/4	1/3	1	4.81%	2.0%

Eigenvalue (λ) = 6.35; Mean Relative error (MRE) of the weights = 37.4%; Geometric consistency index (GCI) = 0.21; and Consistency ratio (CR) = 5.6%.

Table S6. Saaty's Analytical Hierarchy Process (AHP) for Soybean Crop Requirements.

Matrix		**pH_s**	**EC_e**	**SAR**	**OM (%)**	**Avail. P**	**Avail. K^+**	**SSP (%)**	**Texture**	**Slope (%)**	**LU&LC**	**Normalized Principal Eigenvector**	**+/-**
	#	1	2	3	4	5	6	7	8	9	10		
pH_s	1	1	2	1/2	1/3	3	2	3	1	1/4	1/7	6.65%	2.9%
EC_e	2	1/2	1	2	1/3	3	2	2	1/3	1/5	1/5	5.80%	2.8%
SAR	3	2	1/2	1	1/3	2	2	2	1/2	1/3	1/7	5.81%	2.7%
OM (%)	4	3	3	3	1	2	2	5	3	1/2	1/3	13.34%	5.7%
Avail. P	5	1/3	1/3	1/2	1/2	1	1	2	1/3	1/3	1/7	3.80%	1.7%
Avail. K^+	6	1/2	1/2	1/2	1/2	1	1	2	1/3	1/3	1/5	4.14%	1.5%
SSP (%)	7	1/3	1/2	1/2	1/5	1/2	1/2	1	1	1/3	1/7	3.42%	2.1%
Texture	8	1	3	2	1/3	3	3	1	1	1	1/5	9.20%	4.9%
Slope (%)	9	4	5	3	2	3	3	3	1	1	2	19.75%	12.7 %
LU&LC	10	7	5	7	3	7	5	7	5	1/2	1	28.09%	10.7 %

Eigenvalue (λ) = 11.08; Mean Relative error (MRE) of the weights = 48.6%; Geometric consistency index (GCI) = 0.29; and Consistency ratio (CR) = 8.1%.

Table S7. Saaty's Analytical Hierarchy Process (AHP) for Soybean crop land suitability.

Matrix		Land Suitability	Irrigation Water Quality	Climatic Conditions	Normalized Principal Eigenvector
	#	1	2	3	
Land Suitability	1	1	3	1/2	33.25%
Irrigation Water Quality	2	1/3	1	1/3	13.96%
Climatic Conditions	3	2	3	1	52.78%

Eigenvalue (λ) = 3.05; Mean Relative error (MRE) of the weights = 23.0%; Geometric consistency index (GCI) = 0.16; and Consistency ratio (CR) = 5.6%.

Table S8. Overview of Datasets and Thematic Maps, Including Sources, Resolutions, and Relevant Information.

Dataset	Attributes	Resolution	Source	Description and Use
Sentinel-2A Images	Band 2 - Blue (496.6 nm) Band 3 - Green (560 nm) Band 4 - Red (664.5 nm) Band 8 - NIR (835.1 nm)	10 m	USGS (United States Geological Survey)	Multispectral satellite imagery for land use & cover type (crop land, fallow land, barren land, water bodies, built-up area, and vegetation) classification and monitoring.
Digital Elevation Model (DEM)	Elevation (m) Slope (%)	1 arc-second (Approx. 30 m)	USGS (United States Geological Survey)	Elevation data for topographic analysis, slope, and aspect calculations.
NASA Power Data Access Viewer (DAV)	Precipitation (mm) Temperature (°C)	2 m	NASA's POWER project	Historical and real-time precipitation and temperature data for climate change studies.
Soil Map	Soil EC_e (dSm^{-1}) Soil pH_s SAR $(mmol_c L^{-1})^{1/2}$ Organic Matter (%) Available P (mg kg^{-1}) Extractable K^+ (mg kg^{-1}) Soil Saturation (%) Soil Texture a. Sand (%) b. Silt (%) c. Clay (%)	Variable	Ground Truth Data	Information about soil physical and chemical properties for agriculture and land use planning.
Irrigation Water Map	Water pH EC (dS m^{-1}) SAR $(mmol L^{-1})^{1/2}$ RSC (me L^{-1}) Chloride (me L^{-1}) TDS (ppm)	Variable	Ground Truth Data	Information about irrigation water quality for agriculture use.

Table S9. Land suitability classification structure.

Suitability Class	Symbol	Description
Highly suitable	**S1**	It is possible for the land to sustain its use over the long term, with benefits that outweigh the resources invested.
Moderately suitable	**S2**	Although the land may appear appropriate for use, certain constraints may limit its productivity or require greater resources to maintain productivity when compared to S1 land.
Marginally suitable	**S3**	Land that has significant constraints, resulting in reduced benefits and increased input requirements for production, which may only be marginally justifiable in terms of their costs.
Currently not suitable	**N1**	Land that is unable to sustain the intended land use over the long term, or land where the benefits do not outweigh the required inputs.
Permanently not suitable	**N2**	Land that has inherent constraints to long-term sustainable use that cannot be mitigated or overcome.

Table S10. Basic requirements for the cultivation of soybean crop.

Parameters	Value	Reference
Temperature (°C)	10°C (minimum) 24°C (optimum) 36 °C (maximum)	[82, 83]
Precipitation (mm)	400 - 500 mm	[84]
Salinity/EC (dS m^{-1})	5 dS m^{-1} (50% Yield Reduction)	[85]
pH	6.5 - 7.5	[86]
Slope (%)	< 5%	[87]
Texture	Loam	[87]

Table S11. Ten-year climatological met data for temperature (°C) of the study area.

Sr. #	Latitude-Y	Longitude-X	T2M (MAX)	T2M (MIN)	T2M
01	31.3454	73.4298	51.14	-1.68	26.29
02	31.3441	73.4146	49.44	1.08	25.80
03	31.3822	73.3603	49.44	1.08	25.80
04	31.3963	73.4956	49.26	0.84	25.40
05	31.3089	73.4812	49.26	0.84	25.40
06	31.3153	73.3541	49.44	1.08	25.80
07	31.4344	73.5031	49.26	0.84	25.40
08	31.4414	73.3555	49.44	1.08	25.80
09	31.2267	73.5073	49.19	1.18	25.92
10	31.2361	73.3493	49.38	1.83	26.31
11	31.1974	73.431	49.38	1.83	26.31
12	31.3453	73.5636	49.26	0.84	25.40
13	31.3552	73.2896	49.44	1.08	25.80
14	31.48	73.4324	49.44	1.08	25.80
15	31.2126	73.2443	49.38	1.83	26.31
16	31.1439	73.3418	49.38	1.83	26.31

T2M = Temperature (°C) at 2 Meters ; T2M (MAX) = Maximum Temperature (°C) at 2 Meters ; T2M (MIN) = Minimum Temperature (°C) at 2 Meters.

Table S12. Ten-year climatological met data for precipitation (mm) of the study area.

Sr. #	Latitude Y	Longitude X	PRECTOTCOR	PRECTOTCORR_SUM	RH2M	FROST DAYS
01	31.3454	73.4298	1.17	381.27	37.17	0.30
02	31.3441	73.4146	1.47	504.51	42.22	0.00
03	31.3822	73.3603	1.47	504.51	42.22	0.00
04	31.3963	73.4956	1.74	597.75	44.80	0.00
05	31.3089	73.4812	1.74	597.75	44.80	0.00
06	31.3153	73.3541	1.47	504.51	42.22	0.00
07	31.4344	73.5031	1.74	597.75	44.80	0.00
08	31.4414	73.3555	1.47	504.51	42.22	0.00
09	31.2267	73.5073	1.43	477.59	42.09	0.00
10	31.2361	73.3493	1.26	431.92	39.65	0.00
11	31.1974	73.431	1.26	431.92	39.65	0.00
12	31.3453	73.5636	1.74	597.75	44.80	0.00
13	31.3552	73.2896	1.47	504.51	42.22	0.00
14	31.48	73.4324	1.47	504.51	42.22	0.00
15	31.2126	73.2443	1.26	431.92	39.65	0.00
16	31.1439	73.3418	1.26	431.92	39.65	0.00

PRECTOTCORR = Precipitation Corrected (mm/day); PRECTOTCORR_SUM = Precipitation Corrected Sum (mm); RH2M = Relative Humidity at 2 Meters (%).