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Comprehensive Productivity Performance and Environment-Friendly Cultivation of Shallot (Allium ascalonicum L. var. Enrekang) through Integrated Spatial-Temporal Geographic Information System

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Abstract—**Sustainability and inclusivity of the food system are concerned with global hunger closure and are critical to aligning the world's development goals. Boosting crop yields and satisfactory commodity production improves economic-driven productivity, reduces poverty, and guarantees food. This study's primary objective is to represent a significantly, comprehensively, and comparatively assessed productivity performance and environment-friendly cultivation of Shallot (Allium ascalonicum L. var. Enrekang). Hence, we propose a sophisticated geographic information system and technology by integrating in-situ properties and a multispectral-spatial-temporal dataset from Sentinel-2 MSI with a spherical-scale analysis of the Google Earth Engine (GEE). Environtment-physical characteristics of Shallot (Allium ascalonicum L. var. Enrekang) are treated as geology and geomorphology, water resources, soil parameters (permeability, pH, C-organic, soil colour-type), and land use land change (LULC). In contrast, growth performance was observed from 2019 until 2024. Research results show that the number of Shallot crop areas stood at 90% of the vegetation area of 117.56 km² in the Anggeraja sub-district. However, the vegetation area has lost 13,5 % or 101,717 km² in 2024. Environment-friendly cultivation needs productivity harvested area and conservation like terraced in Batu Noni village. Moreover, the optimal temperature for comprehensive productivity performance in shallot plants is between 20° and 30°. The sun's intensity gives 12 hours of exposure in the summer (June-July-August).**

Keywords— **Sustainable agriculture; remote sensing; GIS.**

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I. Introduction

The agricultural sector contributed 12.4% to GDP in 2022, hailing from various sub-sectors such as plantation crops, fisheries, food crops, livestock, horticulture, forestry, and agricultural services [1]. In 2023, the agricultural sector's GDP reached IDR 1,134.5 trillion. Therefore, the number of Agricultural Business Households will expand to 28,419,398 households in 2024 [2]. The productivity and industriousness rate continues to climb the agricultural sector's contribution to the sustainability of the country's economy [3], [4]. Sustainable agriculture aims to view agricultural land as an industry with all factors of production that produce primary food products and other products, including derivative products, by-products, and waste [5]. Food and agricultural policies include diversification of production sources and target the empowerment of swamp land types [6]. Supportable agriculture can comprehensively monitor future productivity performance. Using assistance from the Land Optimization program is one example of a government alliancing to increase national production [7].

Empowering various types of land has been instrumental in improving farmers' welfare, both in terms of income and the expansion of production and competitiveness of agricultural products [8], [9]. Strategic mapping of agricultural development areas is a critical component of plans to support economic productivity in the agricultural sector [10]–[12]. The sector's resilience to commodities, climate change, technology application, and global policies necessitates a modern and environment-friendly approach to agricultural development [13].

The horticultural sector, a beacon of hope in sustainable agriculture, has demonstrated its economic value and productivity potential. As of April 2024, the economic value of horticultural products has skyrocketed by a significant 35 percent compared to April 2023. This remarkable increase in economic value is a clear testament to the sector's productivity potential and considerable contribution to sustainable agriculture. The wide availability of horticultural products further underscores the economic opportunities in this sector, making it a key player in the promising future of sustainable agriculture [14].

Shallot, a superior vegetable commodity, has long been cultivated intensively, and its economic impact on Enrekang's economy is undeniable. In 2023, Enrekang's Red Onion business is projected to reach IDR 3 trillion with a harvest of 145 thousand tons yearly. Recently, at least 1,080 hectares of shallots have been ready to be harvested in the last week of April 2024, further boosting the local economy. The benefit income from shallot cultivation is set to make Enrekang a center of commodities marketed to all regions in Indonesia, supporting national food security and driving Enrekang's economy [15]. The importance of maintaining and increasing the productivity of shallot harvests cannot be overstated. This requires controlling comprehensive productivity performance and environmentally friendly cultivation.

The transformation from traditional processing to the application of agricultural technology meets Indonesia's national needs. Sophisticated GIS technology aids in the preservation and sustainable management of agriculture. By analyzing satellite imagery and agriculture inventory data, GIS can identify areas of potential fertile shallot commodities and support sustainable logging practices[16].

Previous studies focused on traditional product processing, and minimal studies applied GIS to the productivity of shallot harvest mapping in Enrekang. In 2024, Ramadhani et al. reinforced that 83,7% of shallot cropping patterns were detected only on dry upland in Sumenep using three satellite images [7]. Physically, shallot productivity modeling depends on energy productivity, concluded with 95,3% accuracy using CNN. On the other hand, Sulawesi, as a strategically essential food commodity that disregards regional heterogeneity, can overstate or understate welfare loss [13]. To fill these research gaps, we are concerned with comprehensive productivity performance and environment-friendly cultivation of shallot (Allium ascalonicum L. var. Enrekang) through integrated physical parameters and a spatial-temporal geographic information system in Anggeraja Enrekang.

II. Materials and Methods

A. Study Area

Focus study were conducted in Anggeraja is a 3,329 asml highland sub-district in Enrekang Regency, South Sulawesi, Indonesia which is geographically located between $3^0$14'36" – $3^0$50'0" South Latitude and between $119^0$40'53" – $120^0$06'33" East Longitude. Enrekang territorial limits are in North-Tana Toraja Regency, South-Sidrap Regency, East-Luwu Regency, and West-Pinrang Regency. Enrekang district covers approximately 1,786.01 km^2 or 2.83 percent of the area of South Sulawesi Province. This area consists of 12 sub-districts and 129 village/sub-district areas. The area of each sub-district is Maiwa (392.87 km^2), Bungin (236.84 km^2), Enrekang (291.19 km^2, Cendana (91.01 km^2), Baraka (159.15 km^2, Buntu Batu (126.65 km^2), Anggeraja (125.34 km^2), Malua (40.36 km^2), Alla (34.66 km^2), Curio (178.51 km^2), Masalle (68.35 km^2), and Baroko (41.08 km^2) [17].

Highlands is located in Baraka, Anggeraja, Alla, Baroko, and Masalle sub-districts. There are 12 villages of Anngeraja, Tindalun, Bamba Puang, Tanete, Lakawan, Siambo, Singki, Mataran, Pekalobean, Bubun Lamba, Salu Dewata, Mampu, Batu Noni, Saruran, Tampo and Mandatte. In Anggeraja, shallot was planted in the highlands, as were most specialty products of the Enrekang district. Shallot production reached 175.933 tons, with a crop area of 13.699 ha and 7.652 ha of shallot harvest area for vegetable plants. This achievement places Enrekang as the fourth largest producer of shallots nationally after Brebes, Solok, and Nganjuk.

Other types of Anggeraja commodities, harvested areas, and production volumes of these horticultural crops are Shallot harvested area of 7,652 ha as much as 879,980 quintals, Chili harvested area of 26 ha, as much as 3.450 quintals, Potato harvested area of 1 ha, as much as 75 quintals, Cabbage harvested area 23 ha as much as 2.300 quintals, Chinese Cabbage harvested area 12 ha as much as 2,760 quintals, Tomatoes harvested area 92 ha as much as 30,050 quintals, Long bean harvested area 4 ha as much as 300 quintals, Spring onion harvested area 14 ha as much as 1,540 quintals, Carrot onion harvested area 14 ha as much as 3,000 quintals, Squash onion harvested area 14 ha as much as 1,100 quintals, Chili pepper harvested area 34 ha as much as 4,610 quintals, Red bean harvested area 14 ha as much as 1,070 quintal [18].

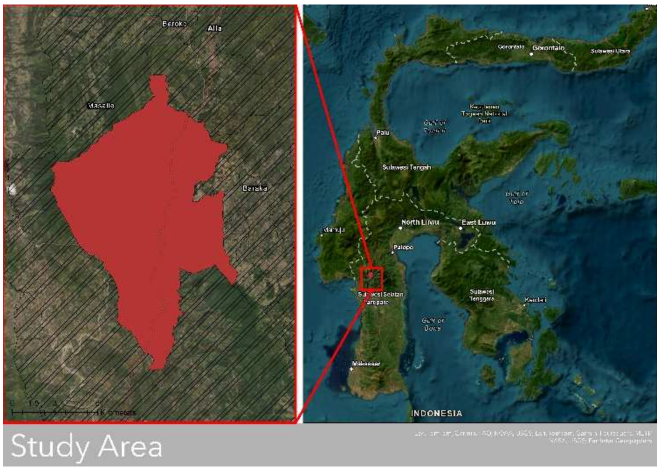

Fig. 1 Research Area in Anggeraja Sub-District

B. Methods

Soil physical conditions bring around plant sprouting and subsequent productivity [19]. Physical parameters consist of water level, water amount, sample weight, soil thickness, soil area, permeability, Soil permeability classes, pH, C-organic, and soil color [20]. Therefore, to increase productivity, explaining the influence of physical parameters on plant productivity is important [21]. Soil permeability (k) or Hydraulic conductivity is interconnected void spaces of soil property and fluid. According to Darcy's law (Laminar'flow), soil permeability ranges from 10-10 cm/sec to 10 cm/sec (10 logarithmic eyeless).

$$k = \frac{(0{,}25 \cdot \pi \cdot D^2)}{(F \cdot (T_1 - T_2))\, ln\left[\frac{H_1}{H_2}\right]} \quad (1)$$

TABLE I

CONTENT OF THE RELATED DATASET

Parameters	Description	Parameter Content	Unit
1	2	3	4
Physical	Overview of sampling site	Shallot-growing region	point
		Sampling point	point
		Geography slope	$(^0)$
	Soil structure of the sampling site per sampling point	Water level	cm
		Water amount	ml
		Soil weight	g
		Soil thickness	mm
		Soil area	cm
		Soil permeability classes	rates
		Permeability	cm/h
		Chemical matter	pH (Acidic-alkaline)
		Soil organic matter	C-organic (l%)
		Soil color	Munsell soil color charts
Spatial-Temporal	Land use characteristics	NDVI	-1 to 1
	Temperature	LST	ºC
		Weather	Seasons

TABLE III

MULTI-TEMPORAL RESOLUTION ON SENTINEL-2 MSI, LANDSAT 9 OLI/TIRS, LANDSAT 8 OLI/TIRS

Satellite Imagery	Resolution			
	Band (B)	Spatial (m)	Spectral (µm)	Temporal (day)
Sentinel-2 MSI	B1 – Coastal aerosol	60	0.443	10
	B2 – Blue	10	0.490	10
	B3 – Green	10	0.560	10
	B4 – Red	10	0.665	10
	B5 – Vegetation Red Edge Band	20	0.705	10
	B6 - Vegetation Red Edge Band	20	0.740	10
	B7 - Vegetation Red Edge Band	20	0.783	10
	B8 - NIR	10	0.842	10
	B8A - Vegetation Red Edge	20	0.865	10
	B9 – Water vapor	60	0.945	10
	B10 – SWIR -Cirrus	60	1.375	10
	B11 – SWIR	20	1.610	10
	B12 – SWIR	20	2.190	10
Landsat series (Landsat 9 OLI/TIRS & Landsat 8 OLI/TIRS)	B1 – Ultra blue (coastal/aerosol)	30	0.435-0.451	16
	B2 – Blue	30	0.452 – 0.512	16
	B3 – Green	30	0.533 – 0.590	16
	B4 – Red	30	0.636 – 0.673	16
	B5 – Near infrared (NIR)	30	0.851 – 0.879	16
	B6 – Shortwave infrared (SWIR) 1	30	1.566 – 1.651	16
	B7 – Shortwave infrared (SWIR) 2	30	2.107 – 2.294	16
	B8 – Panchromatic	15	0.503 – 0.676	16
	B9 – Cirrus	30	1.363 – 1384	16
	B10 – Thermal infrared (TIR) 1	100	10.60 – 11.19	16
	B11 – Thermal infrared (TIR) 2	100	11.50 – 12.51	16

Sentinel-2 is a European high-resolution, specialty in multispectral to high spectral imaging expedition [22]. Sentinel satellite is designed to provide a high revisit frequency over five days at the Equator and ten days to global [23]–[26]. [27]. Sentinel-2 includes 13 spectral bands consisting of 10 m of 4 bands, 20 m of 6 bands, and 60 m of 6 band [28]. The constellation support in Sentine-2A and Sentinel-2B (see Table II).

The normalized Difference Vegetation Index (NDVI) effective index for Shallot's quantifying depends on the green vegetation [29]. NDVI has a principle of the visible light spectrum region capturing green plants grow very effectively by absorbing radiation and reflecting radiation from the near-infrared [30]. The concept of spectral patterns is based on the red band applied method. Interval values of NDVI range -1 to 1 [31]. -1 or Negative values of NDVI generated in water. -0.1 to 0 generally corresponds to bare soil or urban. Around 0.2 to 0.4 represent moderate to intermediate vegetation, while NDVI values are approaching 1, indicating temperate and high-density vegetation such as rainforest ([32]. NDVI formula can be seen in Eq. 2.

$$NDVI = Index(NIR, RED) = \frac{NIR-RED}{NIR+RED} \quad (2)$$

On the other hand, LST indicates the temperature condition of the outermost part of an object on the earth's surface of the energy balance and the main parameters in the physics of land surface processes on a large scale. In a season where the summery weather of the earth's surface, the land surface is practiced as a calm and natural air purifier due to the plant (tree or forest) [33]. LST is calculated using Landsat 8 OLI/TIRS or Landsat 9 OLI/TIRS thermal bands. LST formula can be seen in Eq. 3.

$$LST = \frac{K_2}{\ln\left(\frac{K_1(QCALMAX-QCALMIN)}{(LMAX_\lambda - LMIN_\lambda)(QCAL-QCALMIN))+LMIN_\lambda} + 1\right)} \quad (3)$$

Sentinel-2 Mission with MSI instrument has three kinds of resolutions [34]. First, the temporal resolution of the MSI sensor is the revisit frequency of the satellite to a particular location every ten days revisit [35]. The second spatial resolution of Sentinel 2 MSI Level 1 or Level 2 detected objects on the earth's surface by the satellite sensor array. Complete resolution information is shown in Table II. It represents the MSI-Sensor's ability to distinguish between the earth's surface in the multispectral wavelengths. Lastly, radiometric resolution is the digital quantification level used to express the data collected by a sensor [36]–[38]. The higher the radiometric resolution value, the more detailed information the sensor can collect. Sentinel-2 swath width is 290 km. In comparison, the swath width of Landsat 8 OLI/TIRS and Landsat 9 OLI/TIRS is 185 km of swath width [39].

III. Results and Discussion

Physical parameters were collected from the sampling site of the Shallot-growing region in Anggeraja, which had ten sampling coordinates and ten soil samplings. All sampling data spreads in Anggeraja Highland with a geographical slope. Geographically, location determines soil-water movement and is closely related to the agricultural sector, such as infiltration rate (the downward entry of water into the soil), osmotic forces (dominating the movement of water into roots), excess water or drainage, surface flow, and evaporation. Variations in soil permeability levels are worked on various types of agricultural land use [40].

The characteristics of the physical properties of the soil and the type of land used on the shallot cultivation land in Anggeraja control the production of shallots. The study results showed that all parameters of the physical properties of the soil support the fertility of shallot productivity. Permeability parameters have levels ranging from moderate, moderately rapid, to very fast. There are two shallot plantations with permeability values reaching 74.54 cm/h or falling into the very rapid category. Most of the soil permeability is instance dominance in moderately rapid. Shallots require a lot of water during productivity and bulb onion formation [41].

Soil characteristics based on chemical parameters significantly affect the preparedness of the soil for planting commodities [42], [43]. The chemical elements observed include pH and C-organic. The distribution of pH values for Shallot commodities is at a basic level, pH 6, while the percentage of C-organic values reaches 90% concentration. The values of both parameters support the level of soil fertility seen from the very close relationship between the parameters [21]. Thus, the results of these chemical parameters are expected to increase the productivity and production results of Shallot commodities in Anggeraja. The completion characteristics of physical and chemical parameters are shown in Table III

TABLE IIIII
SHALLOT'S CHARACTERISTICS OF PHYSICAL AND CHEMICAL PARAMETERS IN ANGEGRAJA

P	Coordinate		Slope (m / º)	Water level (cm)	Water amount (ml)	Soil weight (g)	Soil thickness (cm)	Soil area (cm)	Soil permeability classes	Permeability (cm/h)	pH	C-organic (%)	Soil color
	Lat	Lon											
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	-3º22′38″	119º47′56″	583.3 / 158	6.2	1400	101	5.7	134.14	Moderately rapid	9.59	6	90	2.5YR4/3(olive brown)
2	-3º22′37″	119º47′53″	583.3 / 105	6.4	1500	97	5.7	134.14	Moderately rapid	9.95	6	90	10YR3/3(Dark brown)
3	-3º22′33″	119º47′48″	585.4 / 68	5.8	1140	104	5.7	134.14	Moderately rapid	8.35	6	90	10YR4/2(Dark grayish brown)
4	-3º22′31″	119º47′43″	587.4 / 110	5.9	580	98	5.7	134.14	Moderate	4.17	6	90	10YR5/3(Brown)
5	-3º22′30″	119º47′35″	693.2 / 4	6.1	1200	100	5.7	134.14	Moderately rapid	8.35	6	90	10YR5/6(yellowish brown)
6	-3º22′23″	119º47′30″	692.6 / 158	5.7	800	103	5.7	134.14	Moderate	5.96	6	90	10YR5/8(yellowish brown)
7	-3º22′19″	119º47′30″	692.8 / 221	5.8	400	102	5.7	134.14	Moderate	2.93	6	90	10YR6/8(brownish yellow
8	-3º22′17″	119º47′33″	692.1 / 344	5.7	10000	100	5.7	134.14	Very rapid	74.54	5	90	10YR3/6(dark yellowish brown
9	-3º22′37″	119º47′41″	631.5 / 296	5.6	4000	102	5.7	134.14	Very rapid	30.35	7	90	10YR5/6(yellowish brown)
10	-3º22′44″	119º47′46″	632.7 / 141		1200	99	5.7	134.14	Moderately rapid	8.64	7	90	10YR5/8(yellowish brown)

Figure 2 visually illustrates the spatial pattern of NDVI, which represents land use land change (LULC) for Shallot commodities. The images are shown on a vegetation color scale. NDVI reflects the covered density of shallot area to map and classify vegetation types and to detect changes in vegetation cover over time [44]. Representative of LULC of Shallot harvest area from NDVI extraction are categorized into eight classes: no vegetation, bare soil, sparse vegetation, slight vegetation, moderate density, intermediate green vegetation, dense vegetation, and high density [45]. Once these areas are green, the NDVI is given high value or rapid density. Shallot crop area is divided into sections with moderate density, intermediate green vegetation, dense vegetation, and high density, respectively. On the other hand, color-enhanced low NDVI imagery is faded in color, corresponding to no vegetation, bare soil, sparse vegetation, and slight density. Additionally, NDVI monitors the productivity and health of vegetation and identifies areas of stress or damage [46], [47].

Overall, the amount of land used in the Shallot harvest area decreased. The lowest value of NDVI dropped under 0.2 until June 2024. The distribution of the Shallot harvest area can be seen in Fig. 2. In 2019, the number of Shallot crop areas stood at 90% of the vegetation area of 117.56 km^2 in the Anggeraja sub-district. Currently, the vegetation area has lost 13.5 % or 101,717 km^2 of vegetation area (can be seen in Fig. 2.a. and Fig.2.b). Reduction of the area found in Batu Noni village. Batunoni village was identified as 3.55 km^2 with a slope of more than 40%. Hence, the productivity harvested area is less than or needs conservation, such as terraced [48].

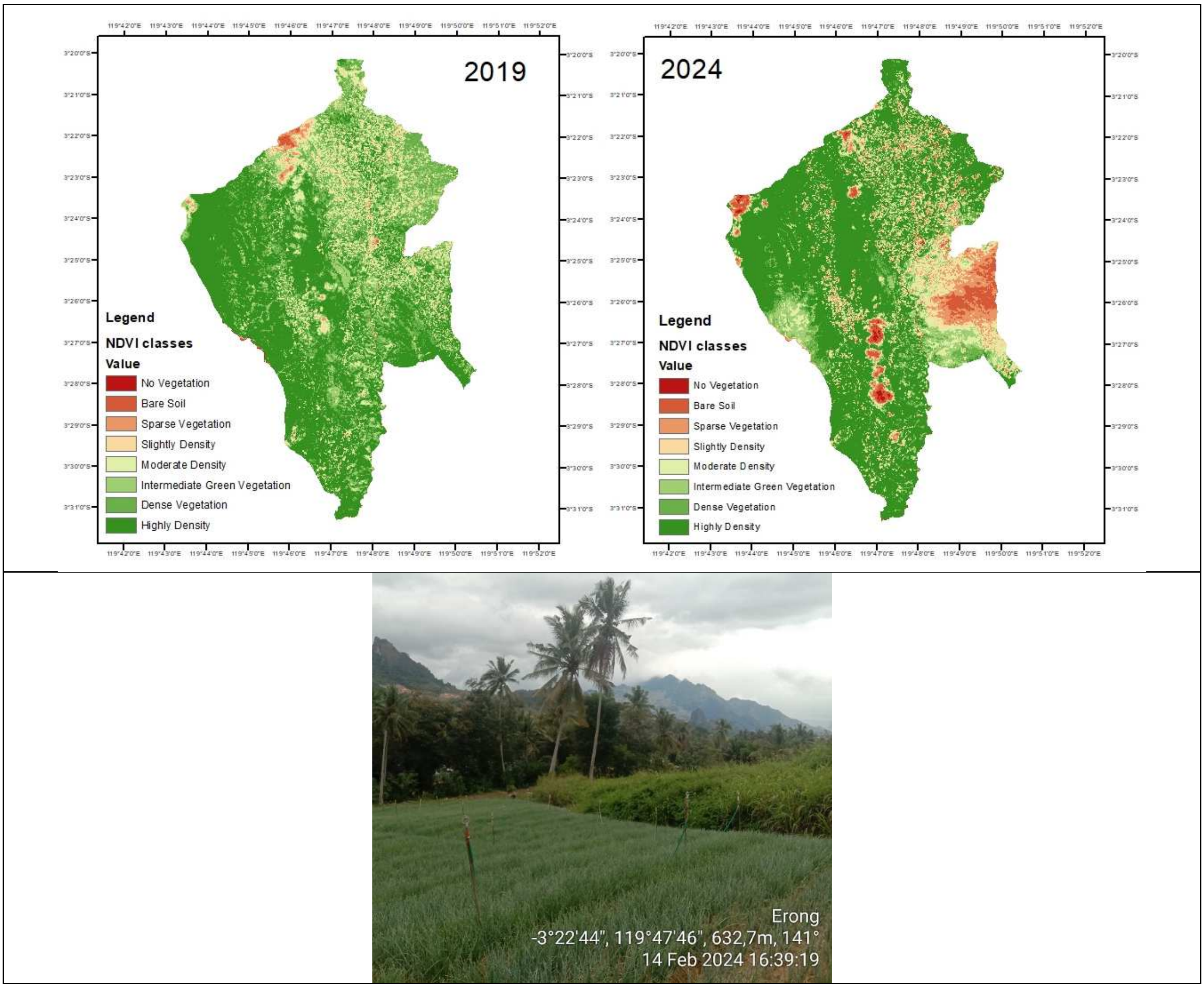

Fig. 2 The vegetation covers changes in Anggeraja using NDVI Sentinel-2 MSI (a) July 2019, (b) June 2024, (c) Shallot observation field in Feb 2024

The graph below shows the harmonic model of shallot's quantifying depending on the greenness index (NDVI) over multiple Sentinel-2 MSI from January 2019 to June 2024. The statistics value of NDVI for Shallot's quantifying in Anggeraja interpolated from 98 satellite imagery of Sentinel-2 MSI is shown in Fig 3 and Table IV.

TABLE IVV
THE CHANGES ON VEGETATION AREA WITH NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI)

	Area (km2)	**Year**	
		2019	**2014**
Class	No vegetation	0.08	0.44
	Bare Soil	0.39	4.64
	Sparse Vegetation	1.30	9.17
	Slightly Density	6.02	9.37
	Moderate Density	12.00	10.57
	Intermediate Green Vegetation	21.32	13.11
	Dense Vegetation	31.25	12.65
	Highly Density	52.99	65.39
Total		**125.34**	**125.34**

Moreover, in shallot plants, the optimal temperature for productivity is between 20° to 30° [49]. The sun's intensity gives 12 hours of exposure in the summer season (June-July-August) (can be seen in Fig. 4) [50]. Shallots grow abundantly in the Anggeraja area, which has a temperate climate in the highlands [51]. Further continental work needs to improve the model and consider the kind of Shallot varieties that affect air quality conditions and urban areas as extracted by other satellite data [52], [53].

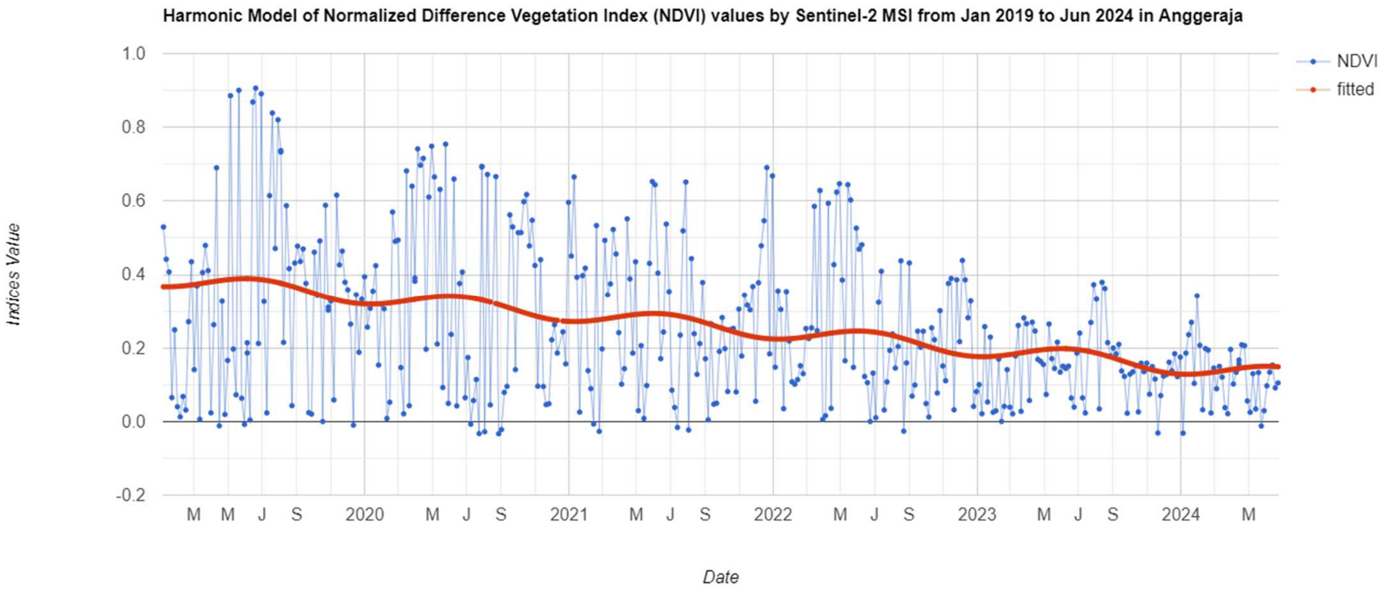

Fig. 3 The harmonic model of Shallot's quantifying depends on the greenness index (NDVI) by Sentinel-2 MSI from January 2019 to June 2024

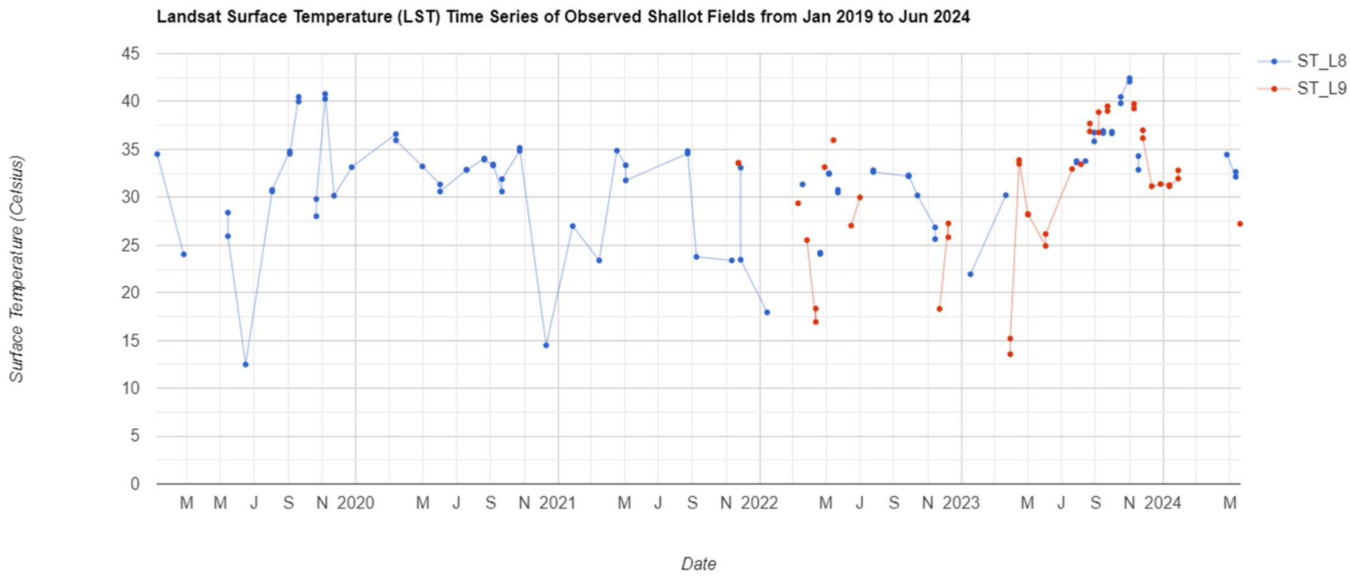

Fig. 4 Landsat Surface Temperature (LST) of Shallot's quantifying on time series from January 2014 to May 2024

IV. Conclusion

The characteristics of the physical properties of the soil and the type of land used on the shallot cultivation land in Anggeraja control the production of shallots. Shallot crop area, Normalized Difference Vegetation Index (NDVI) is given high value or rapid density in sections with moderate density, intermediate green vegetation, dense vegetation, and high density, respectively. On the other hand, color-enhanced low NDVI imagery is faded color corresponding to no vegetation, bare soil, sparse vegetation, and slight density. Shallot harvested areas dropped from 101,717 km2 to 117.56 km2 in 2024 or lost 13,5 % from 2019 to June 2024. Environment-friendly cultivation needs productivity harvested area and conservation like terraced in Batu Noni village. Moreover, the optimal temperature for comprehensive productivity performance in shallot plants is between 20° and 30°. The sun's intensity gives 12 hours of exposure in the summer (June-July-August). Thus, based on observations of physical, chemical, and spatial properties, Anggeraja District is the most suitable area for sustainable red onion harvesting.

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