Vol. 14, No. 3 (2025): 960 - 970 http://dx.doi.org/10.23960/jtep-l.v14i3.960-970

JURNAL TEKNIK PERTANIAN LAMPUNG

ISSN 2302-559X (print) / 2549-0818 (online)
Journal homepage : https://jurnal.fp.unila.ac.id/index.php/JTP

Estimating Crop Water Requirements to Evaluate Cropping Patterns for Agriculture on Post-Tin Mining Land

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Article History:

Received : 24 January 2025
Revised : 09 April 2025
Accepted : 21 April 2025

Keywords:

Agriculture,
Degraded soil,
Irrigation,
Yield.

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ABSTRACT

Utilization of degraded land, such as post-mining land, for agricultural purposes necessitates significant effort, particularly land and water management. This study focuses on estimating crop water requirements (CWR), a crucial step in evaluating suitable cropping patterns for agricultural development on post-tin mining in Bangka Island. The CWR and effective rainfall (EF) of rice, cassava, and peanuts were estimated using meteorological data between 2019 and 2023. The CWR was calculated using Penman-Monteith method, while EF was determined using the USDA SCS Method. The results indicate that average potential evapotranspiration (ET_o) from 2019 to 2023 varied across years. The highest ET_o values were predicted as 5.6 to 5.8 mm/day, while the lowest value was estimated at 4.3 mm/day. Rice and peanut cultivation require supplemental irrigation since EF is insufficient to meet CWR. Cassava, is more suitable, with EF generally fulfilling its CWR. This study provide useful information for developing adaptive strategies that account for the effects of climatic conditions and different cropping pattern, particularly in degraded areas. Furthermore, crop selection that is adapted to the degraded area offers a long-term solution for rehabilitating degraded areas.

1. INTRODUCTION

Mining activities, while economically advantageous, disturb approximately 2 million hectares of land globally each year, equating to about 0.3% of the Earth's surface (Yuan *et al*., 2023). For instance, tin is primarily utilized in the electronics and information technology sectors worldwide. Mines from the Bangka-Belitung Archipelago supply over one-third of the world's tin, which also accounts for 90% of Indonesia's tin production (Maftukhah, Kral, *et al*., 2023). However, mining activities significantly degrade soil health and quality by reducing soil organic carbon (SOC) stocks, diminishing nutrient availability, disrupting soil microbial communities, and lowering enzymatic activities, ultimately creating unfavorable conditions for plant growth (Sae-Tun *et al*., 2024; Yuan *et al*., 2023). Consequently, various strategies have been employed to restore ecosystems degraded by mining, including the use of soil amendments and vegetation restoration.

Recently, regeneration of post-tin mining area for agricultural purposes have been developed by using soil amendments as well as selection of crop species. For instance, combined compost and charcoal improve plant biomass and soil organic carbon in post-tin mining area on Bangka Island (Sae-Tun *et al*., 2024). It is worth noting that agriculture plays an important role on this densely populated island. For example, the rice demand in Bangka Regency is approximately 39,600 tons per year, with about 6,470 tons produced locally, accounting for only 16.3% of total demand. To fulfill this demand, innovations are needed to boost rice production (Syahbudin *et al*., 2022). Developing rice fields on the post-tin mining area is a beneficial practice for improving food supply in the Bangka Belitung Islands, as the majority of staples are obtained from other islands (Nurtjahya *et al*., 2009).

Meanwhile, cassava (*Manihot esculenta* Crantz) plays a crucial role in tropical food security, being widely cultivated as a staple across the Global South (Dettweiler *et al*., 2023). It thrives in limited soil fertility conditions that are associated with subsistence farming and serves as a source of starch and an ingredient for local specialties in Bangka (Maftukhah, Kral, *et al*., 2023). Although cassava can grow under water limited condition, uncertain rainfall events and prolonged drought can induce drought stress, which severely hinders crop performance. Planting cassava at the close of the rainy season typically can lead to the reduction of yields because of water limitation during initial growth (Ruangyos *et al*., 2024). Therefore, ensuring water availability is essential to effectively support agricultural activities in post-tin mining land.

Peanuts (*Arachis hypogea*) can be an affordable source of nutrients such as protein, carbohydrates, vitamins, minerals, and fiber (Settaluri *et al*., 2012). In addition, peanuts have the advantage of being easy to cultivate because they can grow with limited water and fertilizer conditions. Peanuts can obtain nitrogen (N) from the atmosphere through the fixation process and increase the N content in the soil (Dakora *et al*., 1987). This is beneficial for improving soil fertility, especially in post-tin mining land.

The utilization of post-tin mining soil for agricultural purposes is hindered by constraints such as low water retention capacity and exceedingly low water holding capacity (Syahbudin *et al*., 2022). These limitations adversely affect the availability of water in the soil for plant growth. To address this issue, it is imperative to implement a plant selection strategy that aligns with the water availability in the soil. Crop planning based on water availability can be executed to ensure that the water requirements of plants are adequately met while maintaining a sustainable supply of water (Debnath *et al*., 2024). Through effective crop planning, the water needs of plants can be satisfactorily fulfilled without excessive irrigation. Each plant species exhibits varying water requirements dependent on the crop coefficient (Kc) value and evapotranspiration. Selecting plants that match water availability is important to ensure the water needs of plants are met. Rice, for instance, necessitates significant amounts of water for optimal growth, thereby rendering it suitable for cultivation during the rainy season (Kalita *et al*., 2023). In contrast, cassava demonstrates resilience to limited water availability due to its deep root system (El-Sharkawy, 2004). Similarly, peanuts are characterized by their resistance to limited water, although they possess moderate water needs (Sagala *et al*., 2023). These three crop species have been selected to match the availability of water during both the rainy and dry seasons.

Crop water requirement (CWR) is defined as the volume of water needed to replace the water losses in agricultural fields due to evapotranspiration. Factors such as soil type, climate change, topographical location, and crop type significantly influence the quantity of water required by the crop (Gebeyhu *et al*., 2024). Crop Water Requirement (CWR) is important to understand in order to plan planting schedules and determine the amount of irrigation needed (Gautam *et al*., 2019). Furthermore, CWR can indicate whether the water needs of the crops are being met and ensuring optimal yield (Gaddikeri *et al*., 2024). To optimize agricultural production in degraded post-tin mining soils, understanding the crop's water requirements is crucial for identifying favorable environments that promote the maximum growth of selected crop species. Therefore, this study aims to evaluate the water requirements of crops grown in post-tin mining soils and their relationship with water availability. The results of this study could help determine suitable crop patterns for degraded post-mining soils.

2. MATERIALS AND METHODS

2.1. Description of Study Area

The study was conducted on Bangka Belitung Island Province, particularly Bangka Island which is renowned for its tin mining and production. Geographically, this island is located between 1°20'–3°7' South Latitude and 105°–107° East Longitude, with elevations ranging from 50 to 699 meters above sea level (Figure 1). Covering a total area of 11,694 km², Bangka Island is encircled by numerous smaller islands. The climate is characterized by hot temperatures and consistent humidity. The average temperature in 2023 was 27.33°C, with a total rainfall of 1868.44 mm occurring over 213 days (BPS, 2024). Water needs are primarily met through wells and the local water utility (PDAM), but the dry season frequently results in water shortages.

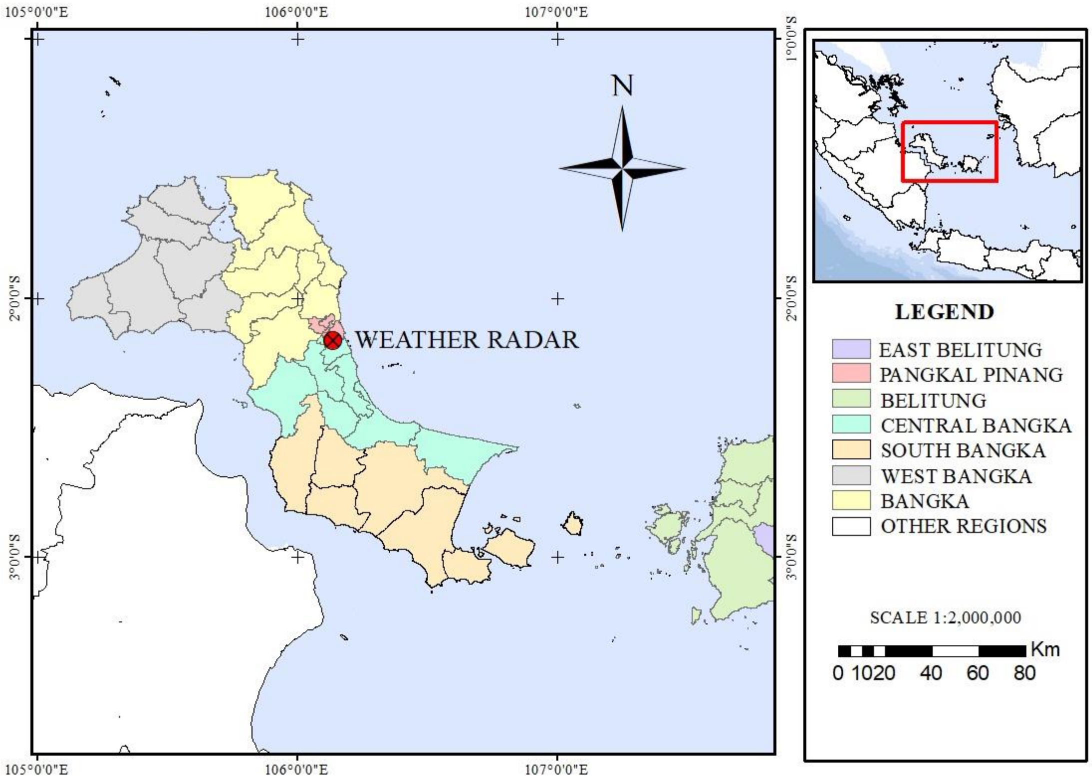

Figure 1. Study site

2.2. Data collection

Climate data were obtained from records collected at the Class I Meteorological Station in Pangkalpinang by BMKG over a 5-year period (2019 to 2023). The climate data used includes rainfall, temperature, humidity, wind speed, and sunshine duration. Through these data, the values of evapotranspiration and effective rainfall can be calculated.

2.3. Data analyses

Evapotranspiration in agricultural fields is influenced by humidity, air temperature, wind speed, and solar radiation, which can be calculated using a few methods, one of which is the Penman-Monteith (PM) (Allen, 1998). Reference evapotranspiration (ET_0) calculated using the PM method was evaluated for its suitability in the area in earlier studies (Hatiye *et al*., 2017; Zotarelli *et al*., 2010). The ET_0 calculated using the PM equation is expressed as:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

where ET_o is reference evapotranspiration (mm/day), Rn is net radiation at the crop surface (MJ/m^2/day), G is soil heat flux density (MJ/m^2/day), T is mean daily air temperature at 2 m height (°C), U_2 is wind speed at 2 m height (m/s), e_s is saturation vapour pressure (kPa), e_a is actual vapour pressure (kPa), (e_s - e_a) is saturation vapour pressure deficit (kPa), Δ is slope vapour pressure curve (kPa/°C), and γ is psychrometric constant (kPa/°C)

The water requirements for crops are determined by the ET_o rate in mm/day, which measures the losses of water from a planted field through evapotranspiration (Hussain *et al*., 2023). Furthermore, evapotranspiration under standard conditions for any crop other than the reference grass, known as potential evapotranspiration (ET_c), is estimated by incorporating a crop coefficient (K_c) into the equation (2) that also used as crop water requirements (CWR).

$$ET_c = ET_o \times K_c \quad (2)$$

The type of crop and its growth stage determine the crop coefficient value (K_c). The values of K_c for every stage of crops were obtained from the FAO Irrigation and Drainage Manual, as shown in Table 1 (Allen, 1998; Doorenbos & Pruitt, 1977). Additional data, including crop growth stage durations, root depth, yield reduction factors, allowable management depletion, and planting and harvesting dates, were also obtained from the FAO Manual.

The USDA SCS method was employed to estimate effective rainfall based on long-term climate data and soil moisture. Effective rainfall was calculated using the total rainfall and monthly consumption shown in Table 2, as well as other storage capacity-based factors in Table 3 (Dastane, 1974). Meanwhile, rainfall for rice crops was estimated using 70% of the average rainfall with a possibility of not being met of 20% (Dirjen SDA, 2013).

Table 1. Crop coefficients for cassva, rice, and peanut.

Half month	Cassava	Rice	Peanut
	i	ii	iii
1	0.3	1.1	0.5
2	0.3	1.1	0.51
3	0.3	1.1	0.66
4	0.3	1.1	0.85
5	0.8	1.1	0.95
6	0.8	1.05	0.95
7	0.8	0.95	0.95
8	0.8	0.95	0.55
9	0.8		
10	0.8		
11	0.8		
12	0.8		
13	0.3		
14	0.3		
15	0.3		
16	0.3		

Note: (i) initial stage: 1-4 half month, mid-season stage: 5-12 half month, late-season stage: 13-16 half month; (ii) initial stage: 1-4 half month, mid-season stage: 5-6 half month, late-season stage: 7-8 half month; (iii) initial stage: 1-3 half month, 4-7 half month, late-season stage: 8 half month.

Table 2. Average monthly effective rainfall (Dastane, 1974)

MCU	Monthly Mean Rainfall (mm)																
	0	12.5	25	37.5	50	62.5	75	87.5	100	112.5	125	137.5	150	162.5	175	187.5	200
	Average Monthly Effective Rainfall (mm)																
25		8	16	24													
50		8	17	25	32	37	46										
75		9	18	27	34	41	48	56	62	69							
100		9	19	28	35	43	52	59	66	73	80	87	94	100			
125		10	20	30	37	46	54	62	70	76	85	92	98	107	116	120	
150		10	21	31	39	49	57	66	74	81	89	97	104	112	119	127	133
175		11	23	32	42	52	61	69	78	86	95	103	111	118	126	134	141
200		11	24	33	44	54	64	73	82	91	100	109	117	125	134	142	150
225		12	25	35	47	57	68	78	87	96	106	115	124	132	141	150	159
250		13	25	38	50	60	72	84	92	102	112	121	132	140	150	158	167

Note: MCU = Mean Monthly Consumptive Use (mm)

Table 3. Multiplication factors (Dastane, 1974)

Effective Storage (mm)	20	25	37.5	50	62.5	75	100	125	150	175	200
Storage Factor	0.73	0.77	0.86	0.93	0.97	1.00	1.02	1.04	1.06	1.07	1.08

3. RESULT AND DISCUSSION

3.1. Land Use in Bangka Island

Land use in the Province of Bangka Belitung Island is predominantly comprised of dryland agriculture and mixed dryland agriculture with shrubs (35.97%), followed by shrubs and swamp shrubs (22.7%), plantations (15.15%), forests (11.8%), mining activities (9.28%), and settlements (2.32%) (Figure 2) (BAPPEDA, 2023).

Agriculture in Bangka Belitung Island holds global recognition for its white pepper products. However, the area of smallholder pepper plantations has been declining steadily, shrinking from 52,688.05 ha in 2019 to 41,749.90 ha in 2023. Correspondingly, pepper production from smallholder plantations has decreased from 33,457.64 tons in 2019 to 24,848.84 tons in 2023 (BPS, 2024).

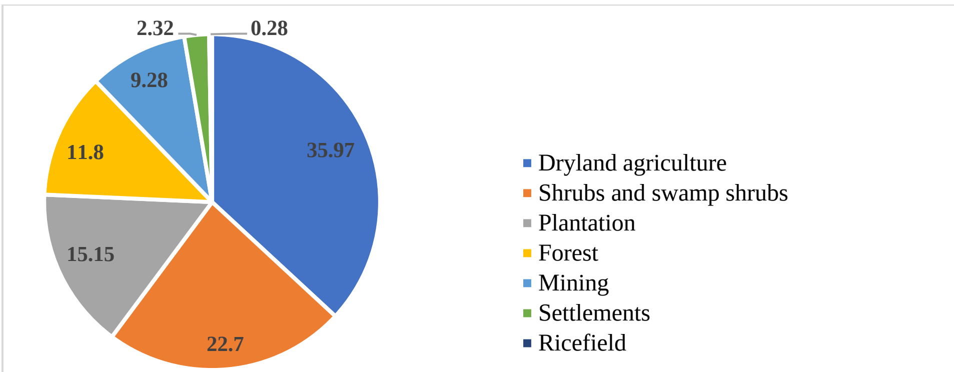

Figure 2. Land use in Bangka Belitung Island Province

The Gross Regional Domestic Product (GRDP) of Bangka Belitung Island reflects the economic performance of the province, driven by key sectors such as agriculture, mining, and services (Figure 3). The economy is significantly influenced by its primary commodities, including tin mining and manufacturing, which have both local and international market value. Additionally, the province's agriculture are growing contributors to its GRDP (BPS, 2024). The local government has recently prioritized agriculture and tourism as the focal points of its development plans, recognizing the declining profitability of land-based tin mining (Maftukhah, Kral, *et al*., 2023). Post-tin mining land in this region remains widespread and largely idle (Anda *et al*., 2022), presenting potential use for agricultural land to support local food security and enhance soil health.

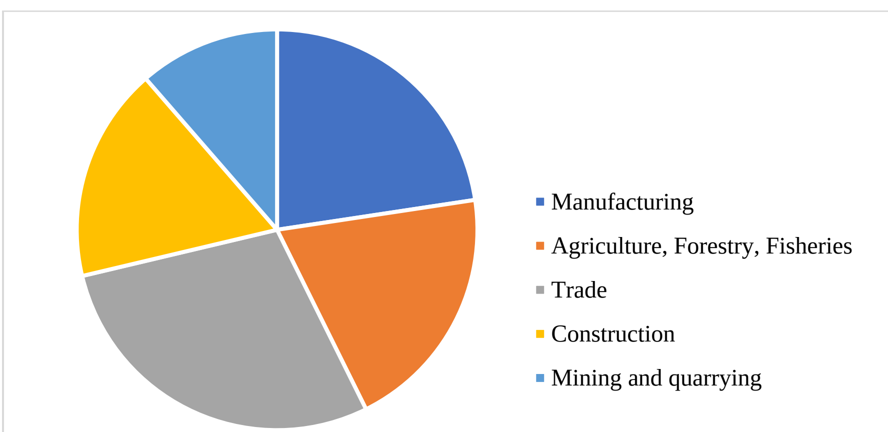

Figure 3. The Gross Regional Domestic Product (GRDP) of Bangka Belitung Island Province

3.2. Reference Evapotranspiration

The average reference evapotranspiration (ET_o) for 2019 to 2023 were different among year (Figure 4). The highest ET_o values were recorded in 2019 and 2023, ranging from 5.6 to 5.8 mm/day, while the lowest was in 2022, at 4.3 mm/day. The variations in ET_o values are influenced by the changing meteorological conditions in the study area. As shown in Figure 4, there is a fluctuation in ET_o values throughout the year, with an increase observed from June to October, influenced by the dry season on Bangka Island. During the dry seasons, the combination of high temperatures, strong winds, and low relative humidity significantly increased ET_o (Hussain *et al*., 2023).

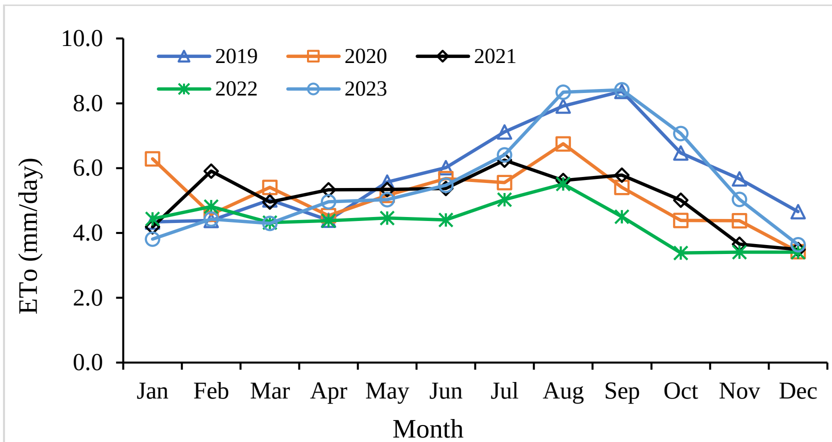

Figure 4. The average daily potential evapotranspiration (ET_o) for the years 2019 to 2023

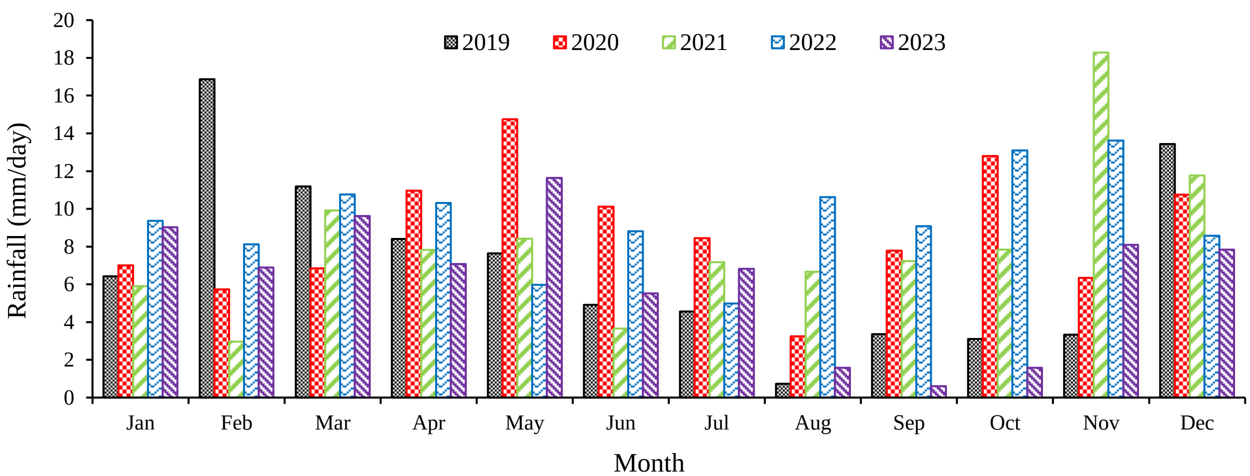

Figure 5. The average daily rainfall for the years 2019 to 2023

Figure 5 presents the average daily rainfall on Bangka Island from 2019 to 2023. The lowest average rainfall was recorded in 2023 (6.4 mm/day), while the highest occurred in 2022 (9.4 mm/day). Each year displayed distinct rainfall patterns, with 2022 being notably rainy throughout the year. According to BMKG, this was attributed to the La Niña phenomenon, which increased rainfall in 2022. High precipitation is one of the most significant impacts of La Niña events. The extreme La Niña event in 2022 was part of a rare "triple-dip" phenomenon, lasting three consecutive years from 2020 to 2023. This event significantly altered both seasonal and annual climate patterns across several equatorial regions (Amanulloh & Romdani, 2024; Shi *et al*., 2023). Figure 6 shows a negative correlation between ET_o and rainfall. The low ET_o values recorded in 2022 were attributed to the year's high rainfall.

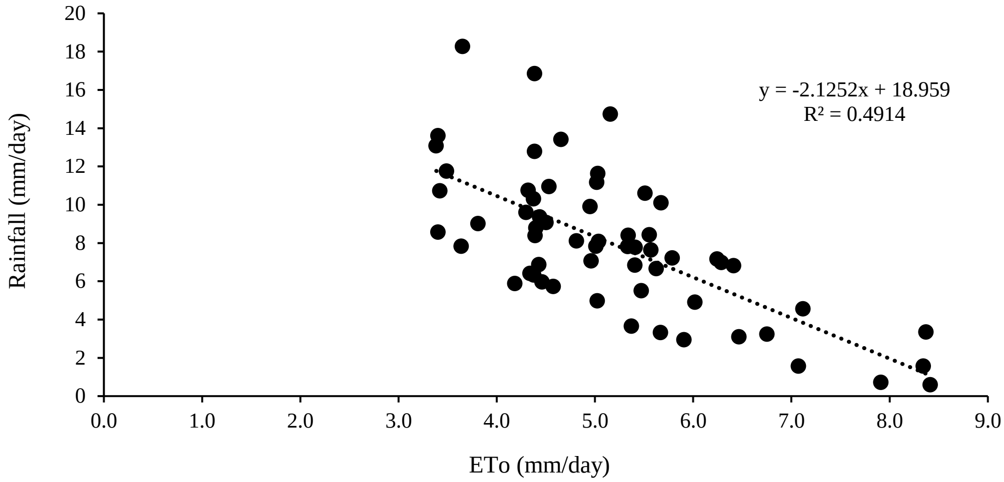

Figure 6. Correlation between potential evapotranspiration and rainfall for the years 2019 to 2023

3.3. Crop Water Requirements and Effective Rainfall

Bangka Island has highly degraded post-tin mining land that potentially use for agricultural development. These lands include water-filled pits, tailings, and former excavation areas. Approximately 10,000 ha of formerly mined areas are planned for rehabilitation (Kral *et al*., 2020). Since 2014, the local government, in collaboration with local farmers, has been developing rice paddies in water-filled pits in Sinar Jaya Village, Bangka Regency. Furthermore, tailing areas also hold potential for cultivating various other agricultural commodities. Post-tin mining land was successfully repurposed for rice cultivation by employing simple technology to integrate rice fields with cow farming, providing a source of organic matter (Su & Lin, 2010). In this study, we calculated the crop water requirement (CWR) for rice fields and tailing areas.

As shown in Table 4, the average daily effective rainfall (ER) for rice cultivation on Bangka Island is generally lower than CWR in both growing seasons. In addition, the seasonal CWR of rice was lower than total ER. The second season of rice has higher CWR than the first season (643 mm and 550.9 mm, respectively) (Figure 7). This result indicates that additional irrigation is necessary to support rice growth and enhance rice productivity in the study area.

The adoption of technologies for managing irrigation, in particular in post-tin mining area, is crucial for improving water use efficiency and supporting rice production. The utilization of post-tin mining water-filled pits for rice irrigation offers a sustainable solution to the challenges of water management in these area. However, the water quality should comply with the regulations for irrigation water quality to ensure the health of crops and prevent soil degradation. In addition, well-designed irrigation systems should be established to ensure efficient water distribution, minimize water loss, and support crop growth throughout the growing season.

The second crop planned to be grown in the rice field after rice as well as in tailing is peanut or other legume species (Table 4). We also found that ER for growing peanut is lower than CWR. Since legume species are adapted to poor soil conditions and serve as an alternative nitrogen source for non-leguminous crops (Maftukhah, Keiblinger, *et al*., 2023), they are an excellent choice for the second crop after rice or in tailing. These legumes can help improve soil fertility by fixing nitrogen, reducing the need for chemical fertilizers and promoting soil health.

Tailing areas need careful selection of suitable plant species due to their limited water holding capacity (WHC) and poor soil fertility. For effective rehabilitation and sustainable land use, planting crop species like drought-resistant plants or legumes can be cultivate on this degraded land.

The present study shows that generally ER for cassava meets the CWR (Table 4), suggesting that this crop is suitable for the areas of Bangka Island. However, during the second period from January to February, ER was lower than CWR, indicating that cassava experience a water deficit and requires additional water supply through irrigation.

In this scenario, cassava was cultivated at the beginning of the rainy season, a growing period of eight months spanning from November of the previous year to June of the next year. In addition, total CWR for cassava is 624.1 mm while total ER is 840.1 mm (Figure 8) indicating that total water availability from rainfall is sufficient for fulfilling CWR of cassava.

Table 4. Average daily crop water requirement of rice, peanut, and cassava

Month		ER (mm/day)			CWR (mm/day)			ER – CWR (mm/day)		
		Rice	**Peanut**	**Cassava**	**Rice**	**Peanut**	**Cassava**	**Rice**	**Peanut**	**Cassava**
Jan	I	7.7	6.7	6.2	4.9	4.2	3.6	2.8	2.5	2.7
	II	3.8	3.8	3.4	5.0	4.5	3.8	-1.2	-0.8	-0.4
Feb	I	1.8	1.9	1.9	4.4	4.4	3.7	-2.7	-2.5	-1.8
	II	3.2	2.9	2.9	4.7	2.7	4.0	-1.6	0.1	-1.1
Mar	I	4.5	4.1	4.1	5.5	2.5	4.0	-1.1	1.6	0.1
	II	5.4	4.3	4.6	5.0	2.3	3.7	0.3	1.9	1.0
Apr	I	5.5	4.5	4.5	4.8	2.9	3.5	0.8	1.7	1.1
	II	3.4	3.5	3.3	5.6	4.3	4.1	-2.2	-0.9	-0.8
May	I	4.1	4.0	3.4	5.5	4.8	1.5	-1.4	-0.7	1.9
	II	3.8	3.8	3.2	5.5	4.9	1.6	-1.7	-1.2	1.6
Jun	I	2.5	2.4	2.1	5.2	5.2	1.7	-2.7	-2.8	0.4
	II	2.6	2.3	2.1	5.0	2.9	1.6	-2.4	-0.6	0.5
Jul	I	1.4	1.2	1.2	6.5	3.0	1.8	-5.1	-1.7	-0.6
	II	2.7	2.5	2.4	6.8	3.2	1.9	-4.2	-0.7	0.5
Aug	I	0.5	0.6	0.6	7.9	4.8	2.2	-7.4	-4.1	-1.6
	II	0.7	0.6	0.5	7.1	5.5	1.9	-6.4	-4.9	-1.4
Sep	I	0.6	0.6	0.6	7.0	6.1	5.1	-6.4	-5.4	-4.5
	II	1.0	1.4	1.3	6.9	6.3	5.3	-5.9	-4.9	-4.0
Oct	I	0.6	0.6	0.6	5.2	5.2	4.4	-4.6	-4.6	-3.8
	II	2.0	2.2	2.3	4.8	2.8	4.1	-2.9	-0.6	-1.8
Nov	I	2.4	2.1	2.1	5.2	2.4	1.4	-2.9	-0.3	0.6
	II	4.1	3.4	3.4	4.2	2.0	1.2	-0.2	1.4	2.2
Dec	I	6.5	5.0	5.0	3.9	2.4	1.1	2.6	2.6	3.9
	II	3.8	3.4	3.2	4.2	3.3	1.2	-0.4	0.2	2.0

Table 5. Monthly crop planned

<table>
<tr><th rowspan="2">Month
Crop
Planned</th><th colspan="2">Nov</th><th colspan="2">Dec</th><th colspan="2">Jan</th><th colspan="2">Feb</th><th colspan="2">Mar</th><th colspan="2">Apr</th><th colspan="2">May</th><th colspan="2">Jun</th><th colspan="2">Jul</th><th colspan="2">Aug</th><th colspan="2">Sep</th><th colspan="2">Oct</th></tr>
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<tr><td>Rice and peanut for rice field</td><td colspan="8">Rice I</td><td colspan="8">Rice II</td><td colspan="8">Peanut</td></tr>
<tr><td>Cassava and peanut for upland</td><td colspan="16">Casava</td><td colspan="8">Peanut</td></tr>
</table>

Intercropping cassava with legumes species may offer significant advantages to enhanced soil health through improved nutrient cycling and greater nutrient use efficiency, as well as broader advantages such as reduced erosion and increased soil coverage (Delaquis *et al*., 2018). Previous studies in the same area investigated an intercropping system of cassava with legume species in post-tin mining areas, focusing on various soil amendment practices to evaluate their effects on yield and drought tolerance (Maftukhah, Kral, *et al*., 2023; Sae-Tun *et al*., 2024). The findings revealed that intercropping with application of soil amendments improved crop yield and reduced drought stress.

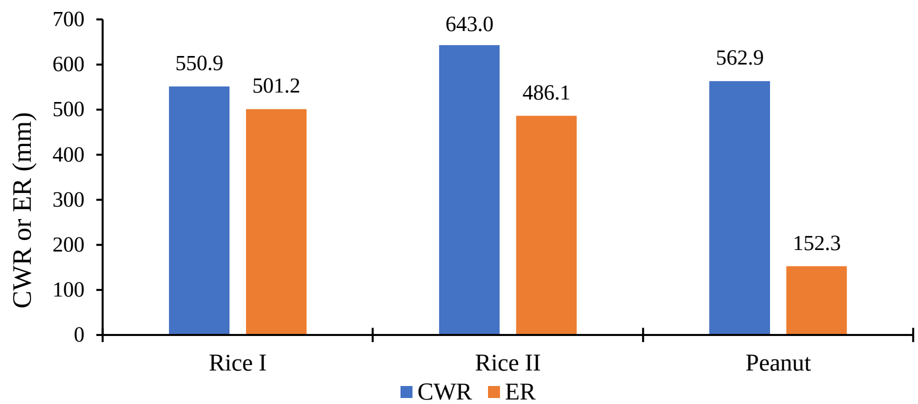

Figure 7. Balance of total crop water requirement (CWR) and effective rainfall (ER) for cropping pattern of rice and peanut

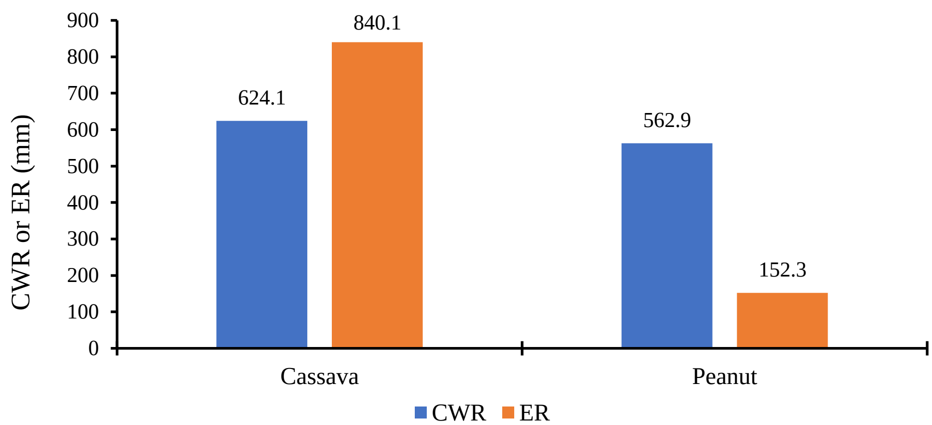

Figure 8. Balance of total crop water requirement (CWR) and effective rainfall (ER) for cropping pattern of cassava and peanut

Overall, both crop planned are still experiencing water deficit conditions indicated by ER < CWR. To address this condition, rainwater harvesting and irrigation can be implemented. This method has been carried out for afforestation in mining areas, which has successfully increased the survival rate of trees to exceed 90% (Liu *et al*., 2022). Rainwater harvesting can be conducted in-situ and ex-situ to address rainfall supply-demand mismatch. The use of plastic mulch can also be combined with rainwater harvesting to maintain soil moisture (Munyasya *et al*., 2022).

4. CONCLUSION

The present study shows that rice cultivation in Bangka Island need additional irrigation as the effective rainfall is generally insufficient to fulfill the crop water requirement for rice growth during both growing season. Furthermore, the effective rainfall for cassava generally meets its crop water requirements, therefore cassava is suitable crop for Bangka Island. The use of post-mining land for agricultural purposes, such as growing rice-rice-peanut for rice field or cassava and legumes for tailing, offers a sustainable solution to rehabilitate degraded areas while promoting food security and economic growth. However, proper irrigation and land management remain crucial for optimizing crop yields in these challenging conditions.

ACKNOWLEDMENT

We express our gratitude to Indonesian Agency for Meteorological, Climatological and Geophysics (Badan Meteorologi, Klimatologi, dan Geofisika or BMKG) for providing online access to climate data.

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