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Agroclimatic Suitability of Biomass Sorghum in West Java, Indonesia: A CLIMEX-Based Study for Renewable Energy Development

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Abstract. *The global demand for renewable energy continues to rise as countries transition from fossil fuels to more sustainable alternatives in response to climate change and energy security concerns. Among various bioenergy sources, high-biomass sorghum (Sorghum bicolor) presents promising potential due to its adaptability, rapid growth, and high biomass yield. This study evaluates the agroclimatic suitability of biomass sorghum in West Java, Indonesia, using the CLIMEX modeling framework to simulate ecoclimatic parameters and growth indices under local climatic conditions. Results show that most regions in West Java—particularly the northern lowlands—exhibit high Ecoclimatic Index (EI) values ranging from 87 to 93, indicating highly favorable conditions for sorghum cultivation. Weekly Growth Index (GIw) simulations reveal optimal growing conditions during the dry season, while certain highland and southern areas face mild limitations during the wet season due to excess rainfall or lower temperatures. Although West Java is broadly suitable for sorghum cultivation, extreme climatic variability—such as heat stress or episodic heavy rainfall—may pose localized challenges to yield stability. These findings provide a scientific foundation for region-specific bioenergy planning and contribute to the strategic development of biomass-based renewable energy in Indonesia.*

Keywords: Sorghum biomass, CLIMEX, Ecoclimatic Index, Bioenergy, Climate modeling, West Java

Introduction

The global demand for renewable energy is increasing as countries work to transition from fossil fuels in order to combat climate change and ensure long-term energy security. Renewable energy sources, such as solar, wind, hydropower, and biomass, are naturally replenished and offer sustainable, environmentally friendly alternatives to conventional energy sources [1]. Among these options, bioenergy—energy generated from biological materials-stands out for its versatility and potential for integration into existing agricultural landscapes [2].

High-biomass crops have gained significant attention within the bioenergy sector due to their ability to produce large quantities of lignocellulosic material, which can be converted into

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bioethanol, solid biofuels, and biogas [3]. High biomass sorghum (Sorghum bicolor) is particularly noteworthy as a promising bioenergy crop. It exhibits remarkable tolerance to abiotic stresses such as drought, salinity, and low soil fertility, making it suitable for cultivation on marginal lands often regarded as unsuitable for food crops [4]. This resilience is especially beneficial in tropical countries like Indonesia, where extensive degraded and marginal land areas can be effectively utilized without jeopardizing food security. In addition to its potential as an alternative food source, sorghum is a valuable raw material for bioenergy production, particularly for bioethanol and solid biomass fuel applications [5].

To optimize the development of bioenergy crops, it is essential to assess their agroclimatic suitability, which refers to the compatibility between climatic conditions and the specific requirements of the crops. An agroclimatic assessment allows policymakers and farmers to identify regions where these crops are likely to thrive under current and future climate scenarios. In this context, computer-based climate modeling tools like the CLIMEX (Climatic Index) model provide a robust approach to predicting the potential geographic distribution of crop species. CLIMEX utilizes key climate variables—such as temperature, rainfall, and humidity—to simulate species responses and generate Ecoclimatic Index (EI) values that quantify habitat suitability [6]. This tool has been successfully applied to map the distribution potential of various agricultural and bioenergy crops across different regions globally.

Despite the growing interest in biomass sorghum for bioenergy production, there is a scarcity of studies assessing its agroclimatic suitability in Indonesia, especially in key provinces like West Java. West Java features diverse topographical and climatic conditions that create both opportunities and challenges for large-scale sorghum cultivation. Therefore, a thorough spatial analysis is necessary to inform land-use planning and guide sustainable bioenergy development.

This study aims to evaluate the agroclimatic suitability and potential implementation of high-biomass sorghum in West Java Province using the CLIMEX model. The findings of this research are expected to provide valuable insights for policymakers, researchers, and stakeholders in developing regionally tailored strategies to support biomass-based renewable energy initiatives, ultimately contributing to national energy resilience and efforts to mitigate climate change.

Theoretical Background

Renewable energy refers to energy obtained from naturally replenishing sources like solar power, wind, water, geothermal energy, and biomass [1]. In contrast to fossil fuels, which are limited and contribute significantly to greenhouse gas emissions, renewable energy presents a sustainable and eco-friendly alternative. The shift towards renewable energy is essential for improving energy security and addressing climate change by reducing carbon emissions [3]. Among the various forms of renewable energy, bioenergy stands out for its flexibility and potential for widespread use. Bioenergy encompasses bioethanol (produced by fermenting sugar- and starch-rich crops), solid biomass (such as wood pellets and agricultural residues), biodiesel (derived from vegetable oils and animal fats), and biogas (produced through the anaerobic digestion of organic waste). Each type of bioenergy has unique benefits and can be applied across sectors such as transportation, electricity generation, and heating [2].

To optimize the cultivation of bioenergy crops like sorghum, the concept of agroclimatic suitability plays a key role. Agroclimatic suitability refers to the compatibility between climate conditions and

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crop requirements, which determines the potential for crop growth and productivity in a given region [7]. One effective tool for assessing agroclimatic suitability is the CLIMEX model. This simulation tool uses climate data to predict the distribution of plant species by calculating an Ecoclimatic Index (EI), which indicates the suitability of a specific area for crop cultivation [8]. Previous studies have demonstrated the application of CLIMEX in mapping the agroclimatic suitability for various crops, including bioenergy species [9]. However, limited research has been conducted on applying CLIMEX for mapping the suitability of sorghum cultivation in Indonesia, particularly in regions like West Java, which presents an opportunity for this study to fill this gap and provide valuable insights for sustainable bioenergy development.

Materials and Methods

This study employed the CLIMEX modeling approach to simulate the potential distribution of high-biomass sorghum (*Sorghum bicolor*) in West Java, Indonesia, based on agroclimatic conditions. CLIMEX integrates climate variables with species-specific biological parameters to predict areas suitable for crop cultivation. The climatic data used in this study included monthly averages of rainfall, maximum temperature, minimum temperature, relative humidity at 09:00, and relative humidity at 15:00, covering a ten-year period from 2010 to 2019. Rainfall and temperature data were sourced from the Climatic Research Unit (CRU TS 4.04), while relative humidity data were obtained from the ERA5 reanalysis dataset. These datasets were spatially interpolated and formatted to align with the input requirements of CLIMEX modeling. Subsequently, the climate variables were calibrated against the agroclimatic parameters of sorghum, including temperature thresholds, moisture requirements, and stress tolerances, based on literature and prior experimental studies. The Ecoclimatic Index (EI) and Growth Index (GI) generated by CLIMEX was used to assess and map the suitability of different regions within West Java for high-biomass sorghum cultivation under current climatic conditions.

The calculation of the Ecoclimatic Index (EI), which reflects the overall climatic suitability for species growth, is described in Equations 1 to 5 [10]. These equations combine key climatic parameters—namely temperature indices, moisture indices, and stress indices—to produce an integrated measure of habitat suitability across different regions.

$$EI = GI_A x \ SI \ x \ SX \quad (1)$$

Where:

EI = Ecoclimatic Index

GIA = Annual Growth Index

SI = Stress Index

SX = Stress Interaction Index

Results and Discussion

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West Java is one of the largest provinces in Java, comprising 18 regencies and nine cities. It is bordered by the Java Sea to the north and the Indian Ocean to the south. According to the administrative map from the Geographic Information Agency (BIG), in 2019, the total area of the West Java region was 3,708,926.21 hectares. This significant land area presents potential for the development of sorghum crops, assuming that land suitability and agroclimatic conditions are favorable. Large tracts of land can be converted into agricultural land for sorghum production, given the right support and conditions.

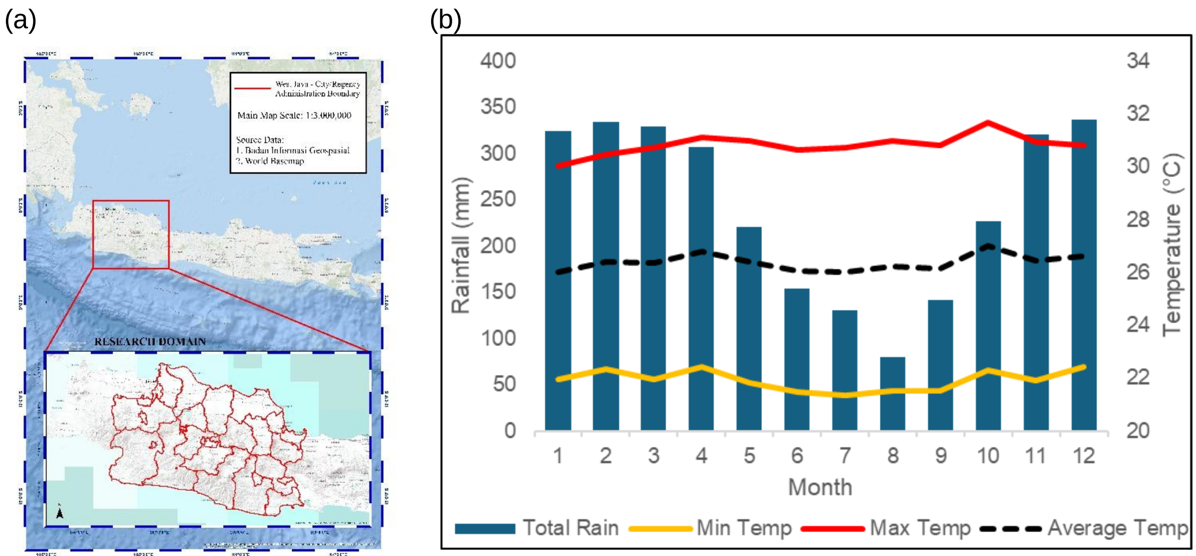

Figure 1. Study area (a) and average climatic condition (b) in West Java from 2010 to 2019

The rainfall graph for West Java Province from 2000 to 2010 illustrates unimodal monsoonal rainfall pattern (**Figure 1**). This pattern is characterized by six months of wet weather and six months of dry weather, with one peak rainy season [11]. The highest monthly rainfall was recorded in January, February, March, November and December, exceeding 300 mm per month. In contrast, rainfall significantly decreased during the dry season months, particularly from June to September, with the lowest value occurring in August, at approximately 79 mm. Meanwhile, air temperature in the region remained relatively stable throughout the year.

Maximum temperatures ranged between 30°C and 32°C, while minimum temperatures varied from 21°C to 23°C. The average air temperature also showed a relatively consistent pattern, ranging between 26°C and 27.5°C, without extreme fluctuations between months. Although the average temperature did not exhibit significant variation, there was a slight decrease observed during the dry season months, especially in July and August. This stability in average temperature reflects the characteristics of a tropical climate, which is generally influenced by monsoonal wind patterns and atmospheric humidity, where climatic variability is more prominently indicated by changes in rainfall than in air temperature.

The primary goal of the compare location function is to assess how suitable a species is for the climate dynamics of a specific region. Key outputs from this function are illustrated in **Figure 3**, which includes the Ecoclimatic Index (EI) and the Growth Index (GI) presented in Table 1. Generally, most sites display high values for both GI and EI, ranging from 87 to 93. According to

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D'Adamo et al. (1998), the EI is categorized into four classes: "unsuitable" for EI values of 0-25, "less suitable" for EI values of 26-50, "suitable" for EI values of 51-75, and "very suitable" for EI values over 75 [12]. In **Figure 2**, we have reclassified the EI values to enhance the visibility of differences among them.

Tabel 1. GI values of CLIMEX modeling results for the period of 2010 to 2019 in West Java Province

No	Location	Alt (mdpl)	Total Rain (Current)	GI	No	Location	Alt (mdpl)	Total Rain (Current)	GI
1	Bandung	728	3016	90	15	Subang	50	1842	92
2	Bandung barat	790	2614	90	16	Sukabumi	300	3158	89
3	Bekasi	18	1942	92	17	Sumedang	450	2704	90
4	Bogor	500	4136	87	18	Tasikmalaya	300	3120	89
5	Ciamis	206	3119	89	19	Kota Bandung	717	2704	90
6	Cianjur	350	3173	89	20	Kota Banjar	200	3262	89
7	Cirebon	10	2593	91	21	Kota Bekasi	11	1864	92
8	Garut	759	3116	89	22	Kota Bogor	265	3632	88
	Indramayu	2	2017	93	23	Kota Cimahi	794	2704	90
9	Karawang	7	1943	92	24	Kota Cirebon	5	2370	92
10	Kuningan	500	2370	92	25	Kota Depok	88	2393	91
11	Majalengka	200	2593	91	26	Kota Sukabumi	584	3632	88
12	Pangandaran	7	2987	90	27	Kota Tasikmalaya	350	2972	90
13	Purwakarta	85	2568	90	15	Subang	50	1842	92
14	Bandung	728	3016	90					

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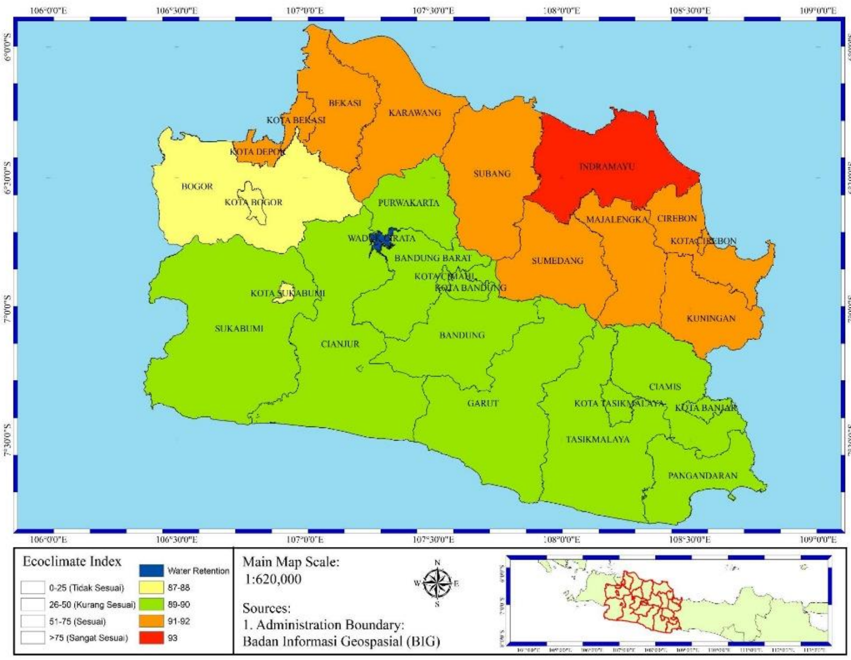

Figure 2. Map of Ecoclimatic Index values from CLIMEX modeling results for the 2010-2019 period in West Java

Bogor District and Bogor City have the lowest Environmental Index (EI) at 87 and 88, respectively, as well as the lowest Growth Index (GI) with the same values. These low indices are likely influenced by urbanization and high rainfall. From 2010 to 2019, the average annual rainfall for Bogor District, Sukabumi City, and Bogor City was 4,136 mm, 3,632 mm, and 3,632 mm, respectively. However, overall, all cities in West Java are classified as highly suitable for planting high-biomass sorghum based on their EI and GI values.

The northern part of West Java exhibits higher environmental index (EI) and geological index (GI) values compared to other regions, particularly in Indramayu, which has both EI and GI values of 93. This trend may be attributed to the relatively higher air temperatures in the northern region of West Java compared to the south. The difference in temperature is influenced by variations in altitude and topography; specifically, for every 100 meters of elevation, the temperature decreases by approximately 0.6°C [13]. The northern region is predominantly characterized by lowlands (0-100 meters above sea level) and is located near the Java Sea, while the southern part is dominated by mountains and highlands. Additionally, the northern area is more open, highly urbanized, and experiences an urban heat island (UHI) effect, which contributes to increased surface temperatures [14].

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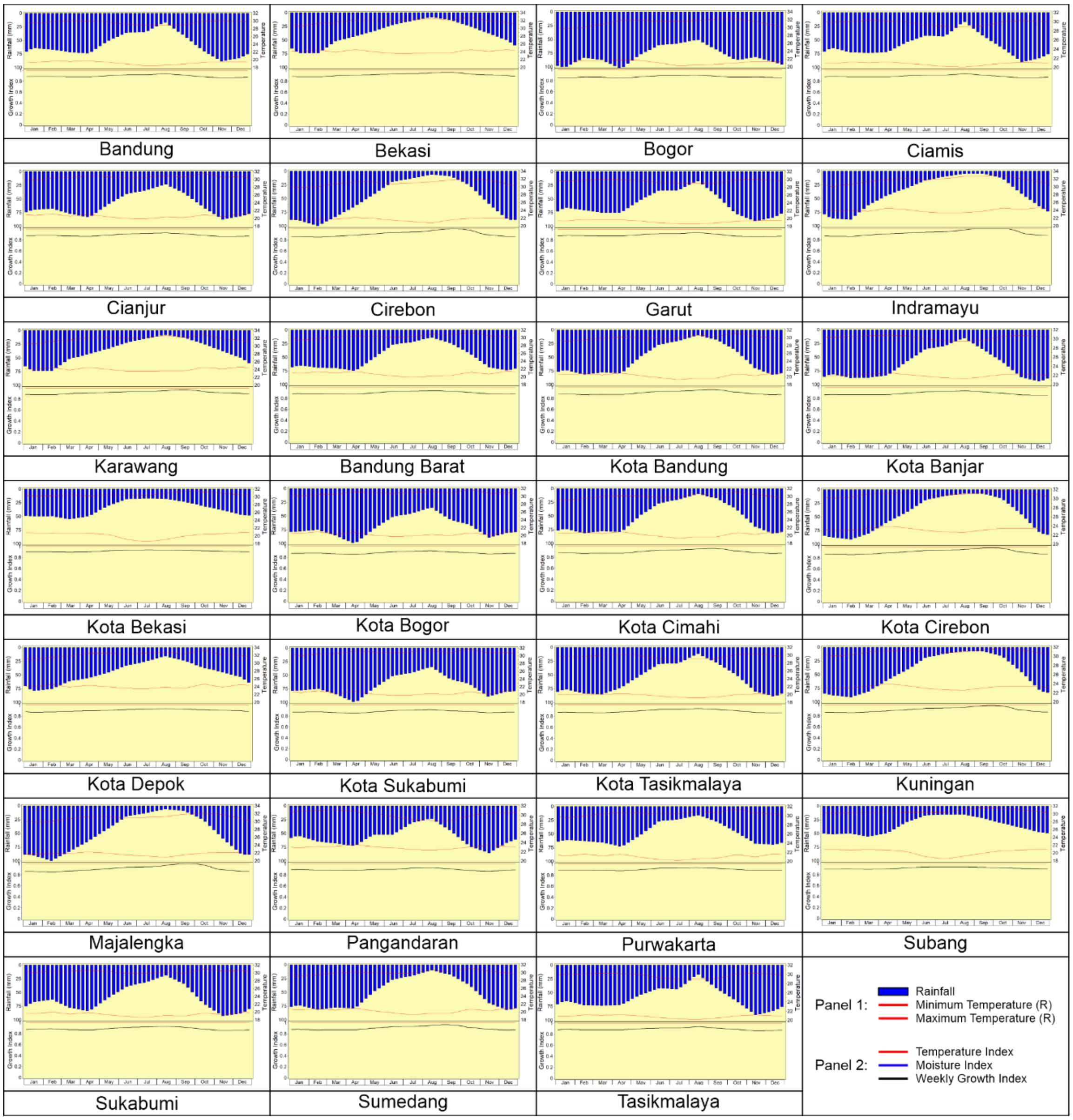

Figure 3. Simulated weekly growth index (GIw) for sorghum across 27 locations in West Java, showing seasonal variation in climatic suitability based on CLIMEX output

Figure 3 presents the Weekly Growth Index (GIw) charts generated by the CLIMEX simulation for 27 cities and regencies across West Java Province. Each chart illustrates the potential growth pattern of sorghum throughout the year, based on climatic parameters such as weekly rainfall, maximum temperature, and the weekly growth index. The GIw is a weekly index indicating the potential growth of a species during a specific week. GIw values range from 0 to 1, where 0 represents conditions unsuitable for growth and 1 indicates optimal growth conditions [10].

In most regions, the GIw pattern shows consistently high and stable values, typically ranging from 0.8 to 1. This reflects that the climate in West Java is generally highly suitable for sorghum

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cultivation, particularly during the dry season—between May and September—when rainfall decreases and temperatures fall within the optimal range for sorghum growth. Conversely, during the rainy season, particularly from December to February, GIw values tend to decline across many areas. This decrease may be attributed to excessive rainfall, which could lead to excessive humidity or plant stress, thereby reducing climatic suitability for optimal growth. However, the decline in GIw during the rainy season is not severe, as several areas still exhibit moderate growth potential.

Regions such as Indramayu, Karawang, Subang, and Bekasi display high and relatively stable GIw values throughout the year, indicating highly favorable climatic conditions for sorghum cultivation, especially during the dry season. Meanwhile, several highland areas such as Cianjur, Garut, and Tasikmalaya show a slight reduction in GIw during the rainy season and early in the year, likely due to a combination of lower temperatures and higher humidity.

Beyond the GIw analysis, extreme value analysis was performed on rainfall and maximum temperature variables to assess climatic variability. The relatively narrow range of EI values (87-93) indicates that the climate in West Java is fairly homogeneous and highly suitable for the growth of high-biomass sorghum, with only minor variations due to local topography. In addition to the CLIMEX simulation, an analysis of climate extremes was conducted to gain a deeper understanding of variability in key climatic factors. Boxplot visualizations were created to assess the distribution and variability of monthly rainfall and maximum temperatures across the study area. This exploratory analysis aimed to identify potential extreme climate conditions, such as unusually low temperatures or high rainfall, that could affect the suitability for sorghum cultivation.

Figure 4 displays the boxplot distribution of monthly rainfall across 27 cities in West Java for the period of 2010–2019. Overall, rainfall patterns show significant spatial and temporal variability throughout the region. In most locations, rainfall peaks during December, January, and February (DJF), which corresponds to the peak wet season. This is reflected in the higher median values and wider interquartile ranges during these months, indicating both increased precipitation and greater variability.

Extreme rainfall variability is particularly noticeable in the whisker length and the presence of outliers, especially during the transitional months of March-April and October-November. This variability suggests occasional extreme rainfall events can impact crop suitability and stress factors in sorghum cultivation. Understanding this intra-annual rainfall distribution is crucial for assessing agroclimatic risks and determining optimal planting times for developing sorghum as a bioenergy crop.

Although the entire West Java region is classified as highly suitable for cultivating high-biomass sorghum based on the Ecoclimatic Index (EI) and Growth Index (GI) values, the potential for extreme rainfall, particularly high extremes, should be monitored. Increased humidity and excessive rain can lead to challenges such as heightened disease prevalence, reduced photosynthetic efficiency, and increased lodging risk, all of which can negatively affect sorghum yields [15], [16]. As illustrated in **Figure 3**, the areas marked with an asterisk—specifically the northern part of West Java, which includes Bekasi Regency, Cirebon, Indramayu, Karawang, Kuningan, Majalengka, Subang, Bekasi City, and Cirebon City—are considered ideal for planting high-biomass sorghum. This assessment is based on their relatively stable rainfall patterns and the absence of extreme values during the period from 2010 to 2019.

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Figure 5 presents the distribution of monthly maximum temperatures from 2010 to 2019 across 27 regencies and municipalities in West Java Province. Overall, the fluctuation pattern of maximum temperatures remains relatively stable throughout the year, though significant variations are observed among different regions. The northern areas, including Bekasi, Karawang, Indramayu, and Cirebon, tend to experience higher maximum temperatures, ranging from 32°C to 35°C all year round. In contrast, the southern regions, such as Garut, Ciamis, Sukabumi, and Pangandaran, show lower maximum temperatures, generally between 28°C and 32°C.

This temperature pattern can be attributed to differences in elevation and geographical location. The northern region of West Java, mainly consisting of coastal lowlands, experiences higher temperatures due to increased solar radiation and lower altitude. On the other hand, the southern region, characterized by mountainous and highland areas, tends to have cooler temperatures due to the cooling effect of elevation [11]. **Figure 5** illustrates the temperature variability in each city across West Java. It can be observed that seasonal variability is consistent across most areas, with maximum temperatures typically rising during the dry season (June–September) and slightly decreasing during the rainy season (November–March). The narrow fluctuations seen in the boxplots also indicate the stability of maximum temperature patterns over the observed decade. Understanding these spatial and temporal patterns of maximum temperature is essential for assessing the agroclimatic suitability of sorghum, as this crop has specific optimal temperature thresholds for its growth and productivity [15].

Sorghum thrives best in a temperature range of approximately 25°C to 35°C, with the optimal maximum temperature typically between 30°C and 35°C. It can tolerate temperatures up to around 38°C [15], [17]. However, it is essential to note that stress can occur when temperatures exceed 38°C for extended periods, especially during the flowering stage. **Figure 4** highlights, with red circles, the regions deemed suitable for sorghum cultivation based on optimal maximum air temperature conditions. These regions include Bekasi Regency, Cirebon, Indramayu, Karawang, and Depok City.

When considering temperature, rainfall conditions become equally important. Sorghum is not well-suited for areas with consistently high annual rainfall exceeding 1000–1200 mm, as excessive moisture can increase the risk of fungal diseases and waterlogging [18], [19]. Therefore, it is crucial to identify regions that fulfill both the temperature and rainfall requirements to maximize biomass yield and ensure sustainable cultivation. This reinforces the importance of agroclimatic modeling approaches, such as CLIMEX, which provide valuable spatial insights for assessing land suitability. In Figures 4 and 5, The overlap of these two markers (asterisk and circle) identifies ideal zones for sorghum cultivation based on an analysis of climate variability and extreme weather conditions. These areas include Bekasi, Cirebon, Indramayu, and Karawang.

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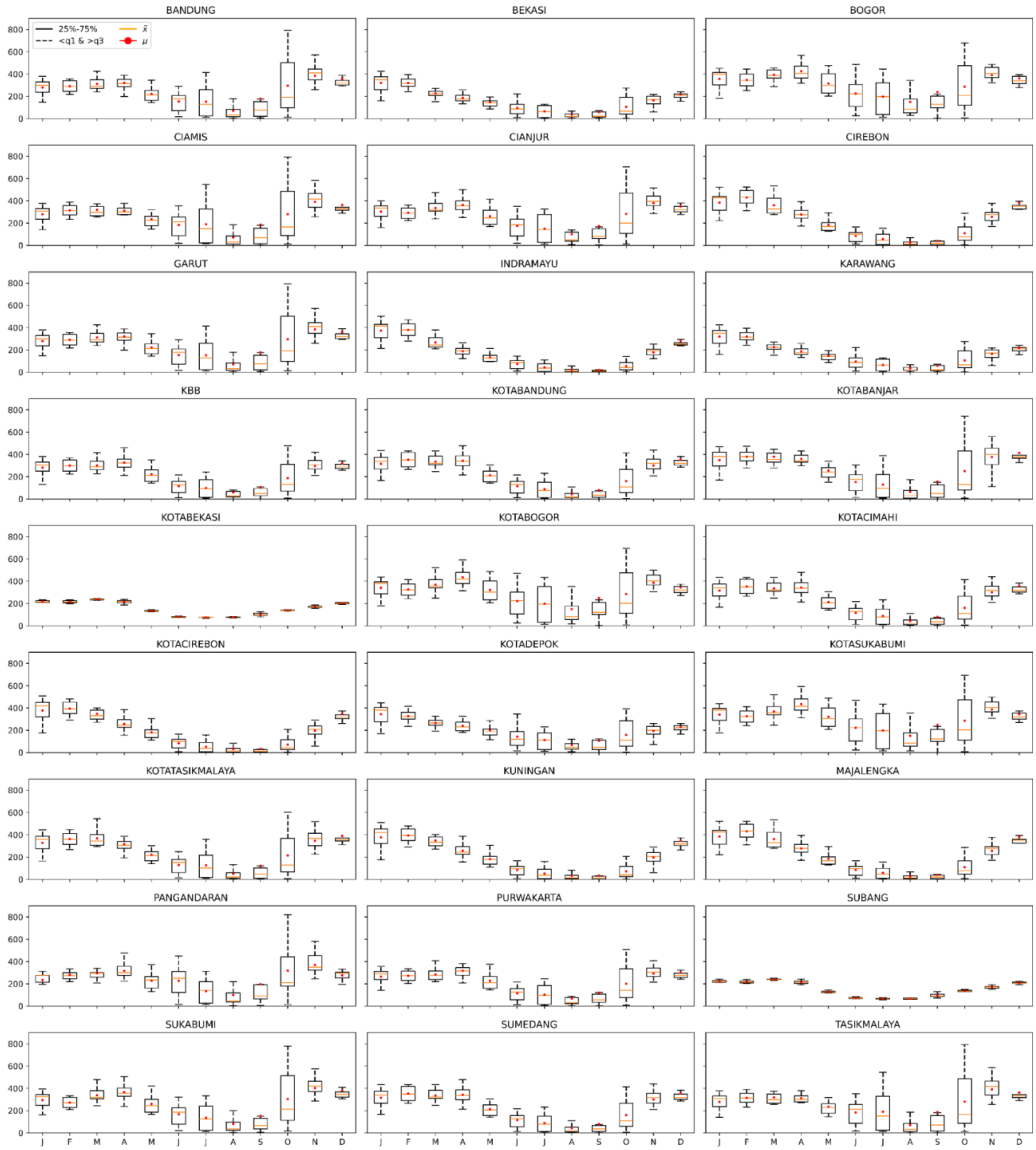

Figure 4. Boxplot of monthly rainfall variability across 27 cities in West Java for 2010–2019

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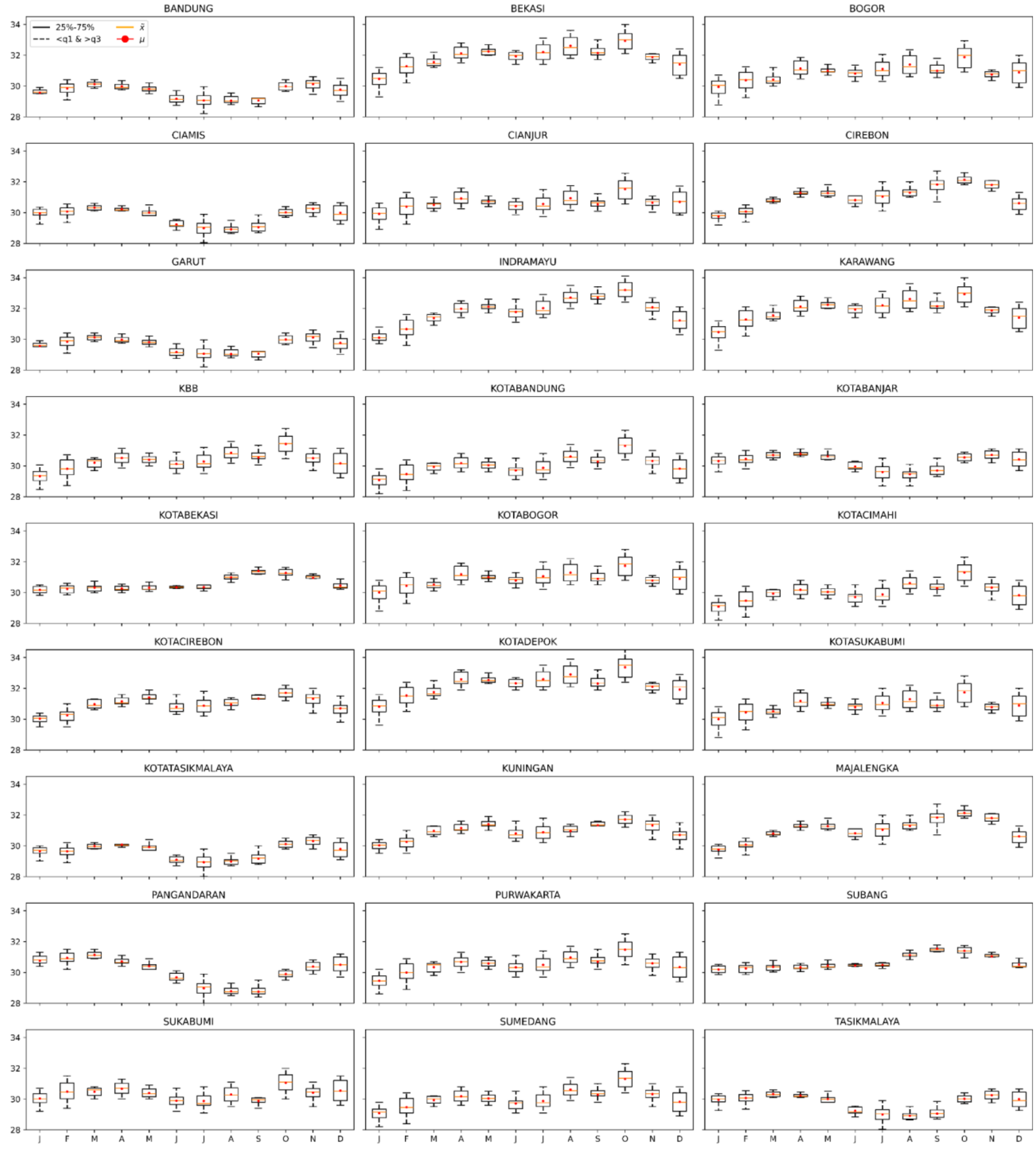

Figure 5. Boxplot of monthly maximum temperatures variability across 27 cities in West Java for 2010–2019

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Conclusions

According to the CLIMEX model analysis, West Java Province demonstrates excellent agro-climatic suitability for high-biomass sorghum cultivation. Most areas in the province receive high Ecoclimatic Index (EI) and Growth Index (GI) values. Weekly GI simulations suggest that West Java's climate is generally favorable for sorghum, especially during the dry season, with only slight limitations in highland areas during the rainy season. The northern part of West Java, including Bekasi, Cirebon, Indramayu, and Karawang, is ideal for sorghum cultivation due to stable rainfall patterns and maximum temperatures that favor growth. However, monitoring extreme rainfall variability and high temperatures in certain regions is essential, as these factors could negatively impact crop productivity and plant health. This study emphasizes the need to monitor extreme climatic events and adopt optimal planting schedules to maximize the potential of sorghum as a bioenergy crop in West Java. These findings provide a potential map for biomass energy supply in West Java, which could be a consideration for planning biomass power plants in the region.

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