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OPTIMIZATION OF HARVEST TIME FOR BIOMASS AND PHYCOBILIPROTEIN PRODUCTION OF *Spirulina* sp. CULTIVATED IN GANYONG (*Canna edulis*) SHOOT WASTE–BASED LIQUID ORGANIC FERTILIZER

Optimasi Waktu Panen untuk Produksi Biomassa dan Fikobiliprotein *Spirulina* sp. pada Media Pupuk Organik Cair Limbah Tajuk Ganyong (*Canna edulis*)

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ABSTRACT

Spirulina sp. is a microalga with high economic value and strong potential as a source of protein and bioactive pigments for functional food, cosmetic and pharmaceutical applications. This study aimed to evaluate the growth performance, protein and pigment contents, and to determine the optimal harvest time of *Spirulina* sp. cultured using liquid organic fertilizer (LOF) produced from fermented ganyong shoot waste (*Canna edulis*). The culture was conducted for 16 days using LOF media at concentrations of 14 and 18 ml/L. The observed parameters included dry biomass weight, specific growth rate, biomass productivity, protein content, chlorophyll-a and phycobiliprotein pigments throughout the cultivation period. The results showed that Spirulina sp. biomass increased by approximately fivefold compared to the initial biomass in both treatments. Specific growth rate, biomass productivity, and protein content did not differ significantly between the two LOF concentrations ($p > 0.05$), with protein content ranging from 42% to 55% of dry biomass weight. Chlorophyll-a and phycobiliprotein contents varied according to the growth phase of the culture. The highest phycobiliprotein content was obtained in cultures grown with 14 mL/L LOF and harvested on day 8 of cultivation. These findings indicate that liquid organic fertilizer derived from ganyong shoot waste has strong potential as a sustainable alternative nutrient source for biomass and pigment production of *Spirulina* sp., with the exponential growth phase representing the optimal harvest time.

Keywords: Ganyong Waste, Growth Media, Liquid Organic Fertilizer, Pigment, *Spirulina* sp.

ABSTRAK

Spirulina sp. merupakan mikroalga bernilai ekonomi tinggi yang berpotensi sebagai sumber protein dan pigmen bioaktif untuk aplikasi pangan fungsional, kosmetik dan farmasi. Penelitian ini bertujuan untuk mengevaluasi pertumbuhan, kandungan protein dan pigmen, serta menentukan waktu panen optimal *Spirulina* sp. yang dikultur menggunakan pupuk organik cair (POC) hasil fermentasi limbah tajuk tanaman ganyong (*Canna edulis*). Kultur dilakukan selama 16 hari menggunakan media POC dengan konsentrasi 14 dan 18 ml/L. Parameter yang diamati meliputi berat kering biomassa, laju pertumbuhan spesifik, produktivitas biomassa, kandungan protein, klorofil-a, serta pigmen fikobiliprotein selama masa pengkulturan. Hasil penelitian menunjukkan bahwa *Spirulina* sp. mengalami peningkatan biomassa hingga sekitar lima kali lipat dibandingkan berat awal pada kedua perlakuan. Laju pertumbuhan spesifik, produktivitas biomassa dan kandungan protein pada kedua konsentrasi POC tidak menunjukkan perbedaan yang signifikan secara statistik ($p > 0,05$), dengan kandungan protein berkisar antara 42–55% dari berat kering biomassa. Kandungan klorofil-a dan fikobiliprotein mengalami perubahan seiring dengan fase pertumbuhan kultur. Kandungan fikobiliprotein tertinggi diperoleh pada media POC 14 ml/L yang dipanen pada hari ke-8 masa pengkulturan. Hasil penelitian ini menunjukkan bahwa POC limbah tajuk ganyong berpotensi sebagai sumber nutrien alternatif yang berkelanjutan untuk produksi biomassa dan pigmen *Spirulina* sp., dengan waktu panen optimal pada fase pertumbuhan eksponensial.

Kata Kunci: Limbah Ganyong, Media Tumbuh, Pigmen, Pupuk Organik Cair, *Spirulina* sp.

INTRODUCTION

Spirulina sp. is a microalga belonging to the Cyanophyta group (blue-green algae) that has long been recognized as a high-value biomass source with significant potential in the food, health, and pharmaceutical sectors (Maddiboyina et al., 2023). This microalga contains various important bioactive compounds such as proteins, essential amino acids, natural pigments, vitamins, minerals, and other functional compounds that provide excellent health benefits for humans (Amir Ali & Bahareh, 2021; Bortolini et al., 2022). In recent years, *Spirulina* sp. has received increasing attention as a raw material for functional foods and nutritional supplements due to the increasing trend in the consumption of plant-based products (Marjanović et al., 2024; Podgórska-Kryszczuk, 2024). One of the main advantages of Spirulina sp. Its very high protein content, ranging from 55–70% of dry weight, with a relatively complete amino acid composition and excellent digestibility of 83–90% (Maddiboyina et al., 2023; Palash et al., 2025). This makes *Spirulina* sp. a potential alternative sustainable protein source to replace animal protein (Grahl et al., 2018). In addition to protein, *Spirulina* sp. also contains chlorophyll-a pigments, phycobiliproteins, and carotenoids, which are used in the food industry as natural dyes and as a raw material in cosmetics as an anti-aging agent, as well as in pharmaceuticals as a bioactive compound with antioxidant, anti-inflammatory, and immunomodulatory activity (AlFadhly et al., 2022; Chini Zittelli et al., 2023).

The growth and biochemical composition of *Spirulina* sp. is strongly influenced by environmental and nutritional factors, including pH, temperature, light intensity, salinity, and the availability of macro- and micronutrients in the culture medium (Ndjouondo et al., 2017). Differences in culture conditions, particularly nutrient types and sources, have been shown to influence the accumulation of pigments, proteins, and other bioactive metabolites (AlFadhly et al., 2022). In general, *Spirulina* sp. can be cultured at various scales, from laboratory scale, semi-mass scale, to mass scale, either open or closed, using photobioreactors (Selvendran, 2015; Zhu et al., 2020). The culture process generally begins with the provision of a pure culture on a laboratory scale, which is then gradually increased in volume until it reaches production scale (Borowitzka, 2016). In efforts to develop sustainable production, the use of economical and environmentally friendly alternative nutrient sources based on organic waste is a focus of current research.

The use of liquid organic fertilizer (POC) from fermented agricultural waste as a microalgae culture medium is a circular economy approach that allows for a reduction in waste treatment costs while providing a carbon-rich substrate for microalgae biomass production (Scarponi et al., 2024). The use of fertilizer media as a nutrient source has also been shown to optimally support the growth phase of *Spirulina* sp., with the highest biomass accumulation generally occurring in the exponential phase to the beginning of the stationary phase (Prasadi, 2018). Previous research reported that *Spirulina* sp. can grow well on POC-based media from ganyong (*Canna edulis*) plant crown waste, which has not been optimally utilized (Wijihastuti et al., 2020). This study examined the cultivation of *Spirulina* sp. using POC from canna crowns at various concentrations and showed that POC concentrations of 14 and 18 mL/L produced the best growth of *Spirulina* sp. compared to other concentrations. Based on these findings, this study is a continuation of the research by Wijihastuti et al. (2020), focusing on the use of POC at these two optimal concentrations. This study aims to assess the growth of *Spirulina* sp. and determine the optimal harvest time when cultured at the best concentration of organic fertilizer (POC), particularly in relation to biomass utilization and accumulation of high-value pigments. In addition to nutritional factors, harvest time, which reflects the growth phase or age of microalgae biomass, including *Spirulina* sp., is also an important determinant of biomass biochemical composition (Hotos & Antoniadis, 2022; Muys et al., 2024). Therefore, research on the effect of harvest time on the pigment content of *Spirulina* sp. cultured using POC from fermented canna plant crowns is necessary as an effort to optimize the production of high-value pigments.

METHODS

Research Location and Time

This research was conducted over three months in the Biology Study Program Laboratory, Faculty of Science and Technology, Al Azhar University of Indonesia. Research activities included the production of liquid organic fertilizer (POC), culturing *Spirulina* sp., growth observation, and analysis of protein and pigment content.

Equipment and Materials

This research used a closed fermentation vessel equipped with an aerator, analytical balance, centrifuge, vortex mixer, water bath, UV–Vis spectrophotometer, fluorescent lamp, and standard laboratory glassware. The materials used included a pure culture of *Spirulina* sp., ganyong (*Canna edulis*) shoots, brown sugar, EM4 as a fermentation starter, clean water, and absolute methanol.

Research Design

This study used a Completely Randomized Design (CRD) with three replications. The treatments consisted of two types of culture media: liquid organic fertilizer (POC) with the best concentration based on previous research. The liquid organic fertilizer was prepared following the method of Pardosi et al. (2014). A total of 1.56 kg of canna shoots were finely chopped and placed in a closed fermentation vessel. Then, 3.94 g of brown sugar, 15.63 mL of EM4, and 2.38 L of clean water were added. The mixture was fermented for 14 days in the dark at 30–50°C, with aeration to accelerate the fermentation process.

The concentration of POC used in this study was based on previous research by Wijihastuti et al. (2020), which reported that POC concentrations of 14 and 18 mL/L provided the best growth rates for *Spirulina* sp. Therefore, this study used only these two concentrations to observe the growth patterns, growth phases, and optimal harvest time for *Spirulina* sp. biomass.

The *Spirulina* sp. culture was first propagated to a density of approximately 1000 units/mL, then used as inoculum in the treatment cultures. The final culture volume was 1 L, grown under T5 LED cool white lighting with an intensity of around 2500 lux with a photoperiod of 12:12 hours (light:dark), aerated and grown for 16 days.

Growth observations were conducted every two days until the end of the culture period. *Spirulina* sp. growth was analyzed based on dry biomass weight. The specific growth rate (μ) of *Spirulina* sp. was calculated based on the increase in biomass dry weight during the exponential phase using the equation $\mu = (\ln(X_2/X_1))/(t_2 - t_1)$, where X_1 and X_2 are the biomass dry weight (g/L) at time t_1 and t_2 (days), respectively. Biomass productivity was calculated as the difference in biomass dry weight at the end and beginning of culture per unit culture time.

Spirulina sp. protein content was analyzed using the method of Lowry et al. (1951) at the end of the exponential phase with bovine serum albumin (BSA) as a standard. Samples were reacted sequentially with 1 N NaOH, Lowry reagent (Na_2CO_3, $CuSO_4$, and $NaKC_4H_6O_6$), and Folin–Ciocalteu reagent, then incubated according to the procedure. Absorbance was measured at a wavelength of 750 nm, and protein content was determined based on a BSA standard curve (0–100 μg/mL) using linear regression.

Biomass was harvested for pigment content analysis every four days. Based on previous research, this time interval was chosen because it represents the conditions of *Spirulina* sp. cultures at different growth phases. Chlorophyll-a analysis was performed using the method referred to by Ritchie (2006). A 10 mL culture was centrifuged at 8,000 rpm for 15 minutes, then the pellet was extracted with 10 mL of absolute methanol and incubated in a water bath at 70°C for 10 minutes in the dark. After vortexing and re-centrifuging, the absorbance of the supernatant was measured at 665 nm using a spectrophotometer. Chlorophyll-a content was calculated using the equation: Chlorophyll-a (mg/mL) = 12.9447 × A665.

Phycobiliprotein analysis was performed using the method based on Bennett & Bogorad (1973) with modifications by Agustini (2012). A 10 mL culture was centrifuged at 8,000 rpm for 15 minutes, then the sample was frozen for 24 hours at −20°C and thawed again at room temperature. The sample was re-centrifuged, and the absorbance of the supernatant was measured at 562 nm, 615 nm, and 652 nm. Pigment content was calculated using the following equation: Phycocyanin (mg/mL) = (OD615 nm - 0.474 OD650 nm) / 5.34; Allophycocyanin (mg/mL) = (OD652nm - 0.208OD615nm)/ 5.09; Phycoerythrin (mg/mL) = (OD562nm - 2.41[Phycocyanin] – 0.849[Allophycocyanin])/ 9.62.

RESULTS

Characteristics of Liquid Organic Fertilizer (POC)

The liquid organic fertilizer (POC) produced after 14 days of fermentation of canna shoot waste showed a mature state. This was indicated by the brownish color of the solution and the characteristic fermentation aroma without any foul odor. With these characteristics, this POC is suitable for use as a culture medium for *Spirulina* sp.

Spirulina sp. Growth

The growth of *Spirulina* sp. in the canna shoot waste POC medium at concentrations of 14 and 18 ml/L was demonstrated by an increase in biomass dry weight during the culture period, as seen in Figure 1. The results of *Spirulina* sp. dry weight measurements showed that the culture with the 18 mL/L POC medium experienced a lag phase of six days, longer than the culture with the 14 mL/L POC medium, which lasted four days. The culture in the 14 mL/L POC medium entered the stationary phase earlier, on day 14, while the culture with the 18 mL/L POC medium entered the stationary phase earlier, on day 16. Both treatments exhibited an exponential growth phase lasting eight days. Cultures in 14 ml/L POC medium reached maximum growth earlier, on day 12, with an average maximum dry biomass weight of 0.5033±0.0006 g/L. Cultures in 18 ml/L POC medium reached maximum growth on day 14 and showed a higher average maximum dry biomass weight of 0.5750±0.0013 g/L. By the end of the culture period, the dry biomass weight had increased approximately fivefold compared to the initial weight.

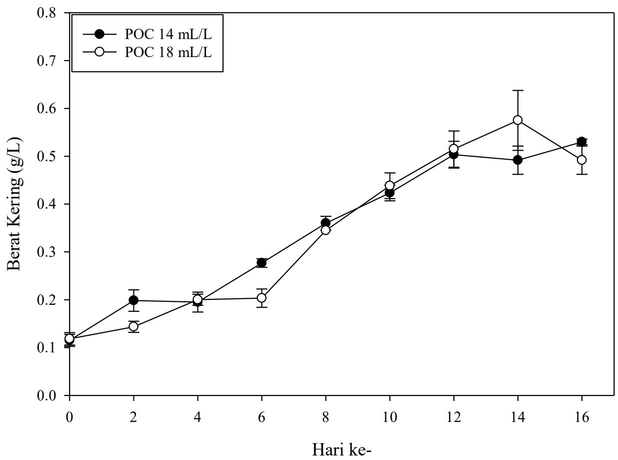

Figure 1. Growth Curve Graph of *Spirulina* sp. at Two Concentrations of POC from Ganyong Waste Based on Biomass Dry Weight. Values are Presented as Averages (n=3) with Error Bars.

The specific growth rate and biomass productivity of *Spirulina* sp. in 14 and 18 ml/L POC media are shown in Table 1. The specific growth rate and biomass productivity in both treatments were relatively similar. The results of the statistical analysis using ANOVA showed that the differences in specific growth rate and biomass productivity between the two concentrations of canna crown POC were not statistically significant ($p > 0.05$).

Table 1. Specific Growth Rate, Biomass Productivity, and Protein Content of *Spirulina* sp.

POC Concentration (ml/L)	Specific Growth Rate (/day)	Biomass Productivity (g/L/day)	Protein Content (mg/L)
14	0.1197±0.0156[a]	0.0269±0.0021[b]	0.2401±0.0546[c]
18	0.1297±0.0126[a]	0.0326±0.0045[b]	0.1957±0.0074[c]

Note: Values are presented as mean ± standard error (n = 3). Values followed by the same letter in the same column indicate no significant difference based on ANOVA ($p > 0.05$).

The protein content of *Spirulina* sp. was measured on day 11 of the culture period, when the *Spirulina* sp. culture was nearing the end of the exponential phase. The protein content in the culture with 14 ml/L POC medium tended to be higher than that in the culture with 18 ml/L POC medium, as shown in Table 1. However, statistical test results indicate that the difference in protein content between the two treatments was not significant. Based on a comparison of protein content with the average dry weight of biomass on days 10 and 12, the protein content of *Spirulina* sp. in the 14 ml/L POC medium reached approximately 55%, while in the 18 ml/L POC medium it was 42% of its dry weight.

Pigment Content of *Spirulina* sp.

Changes in Chlorophyll-a Content of *Spirulina* sp. during the culture period can be seen in Figure 2. At both concentrations of canna shoot POC, the chlorophyll-a content was higher on day 8 than on day 4. On day 12, the chlorophyll-a content in the 14 ml/L POC medium decreased, while the 18 ml/L POC medium still showed an increase. The statistical analysis results showed that the difference in chlorophyll-a content between the two treatments was not statistically significant ($p > 0.05$).

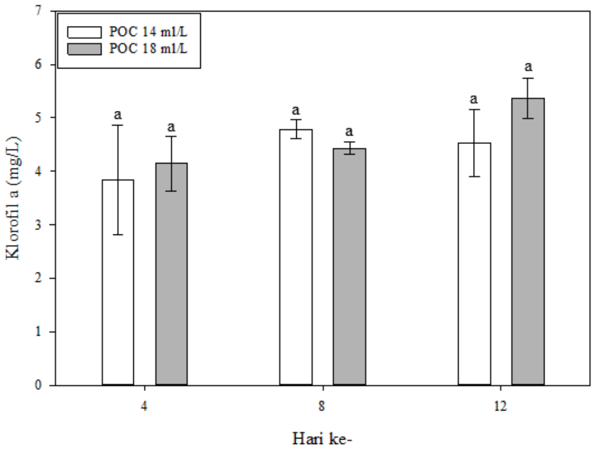

Figure 2. Graph of Chlorophyll-a content in *Spirulina* sp. at Two Concentrations of Ganyong Waste POC Harvested on Different Days. Values are Presented as Means (n=3) with Error Bars. The Same Letter Above the Graph Indicates No Significant Difference Based on ANOVA ($p > 0.05$).

Changes in the phycobiliprotein pigment content of *Spirulina* sp. during the culture period can be seen in Figure 3. The phycocyanin content at both concentrations of canna crown POC increased from the lag phase (day 4) to the exponential phase (day 8), then decreased at the end of the exponential phase (day 12). The patterns of allophycocyanin and phycoerythrin changes differed between treatments. In the 14 ml/L POC medium, allophycocyanin and phycoerythrin content increased until day 8 and decreased on day 12. Conversely, in the 18 ml/L POC medium, both pigments decreased on day 8 and increased again on day 12.

The total phycobiliprotein content showed a pattern of change consistent with changes in its constituent pigments, particularly allophycocyanin and phycoerythrin. Statistical test results showed that changes in phycobiliprotein pigment content were generally not statistically significant, except for the phycoerythrin content in the 14 ml/L POC medium, which increased significantly from day 4 to day 8. The highest phycocyanin, allophycocyanin and phycoerythrin content in 14 ml/L POC media was obtained on the 8th day of the culturing period. In 18 ml/L POC media, the highest phycocyanin content was obtained on the 12th day, while the highest allophycocyanin and phycoerythrin content was obtained on the 4th day.

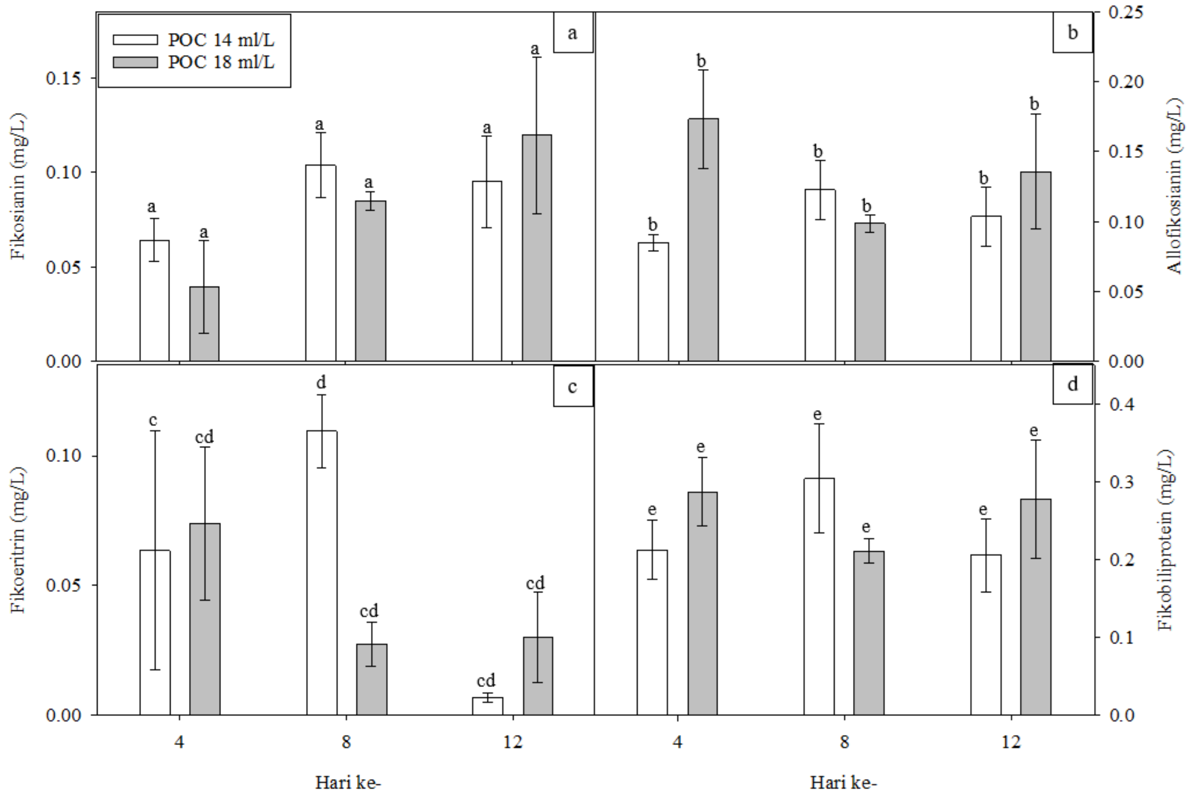

Figure 3. Graph of Phycocyanin (a), Allophycocyanin (b), Phycoerythrin (c), and Total Phycobiliprotein (d) Content in *Spirulina* sp. at Two Concentrations of Organic Fertilizer (POC) from Ganyong Waste Harvested on Different Days. Values are Presented as Means (n=3) with Error Bars. The Same Letter Above the Graph Indicates No Significant Difference Based on ANOVA ($p>0.05$).

The ratio of phycocyanin to allophycocyanin in *Spirulina* sp., which indicates adaptation to light and environmental stress during the culture period, is shown in Figure 4. On day 4, culture with 14 ml/L POC medium showed a higher ratio than that with 18 ml/L POC medium. On days 8 and 12, the ratio values in both treatments were relatively stable. The statistical analysis results showed that the difference in the phycocyanin to allophycocyanin ratio between the two concentrations of organic fertilizer from canna shoot was not statistically significant.

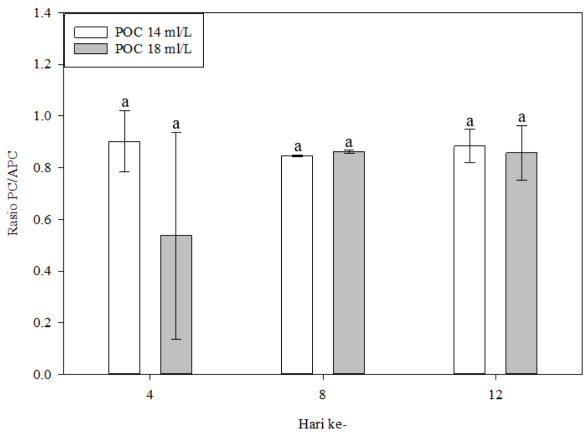

Figure 4. Graph of the Ratio of Phycocyanin (PC) and Allophycocyanin (APC) in *Spirulina* sp. at Two Concentrations of POC from Ganyong Waste Harvested on Different Days. Values are Presented as Mean ± Standard Error (SE) (n=3). The Same Letter Above the Graph Indicates No Significant Difference at the $\alpha = 0.05$ Test Level.

DISCUSSION

The Effectiveness of Fermented Liquid Organic Fertilizer (POC) from Ganyong Waste as a Growth Medium for *Spirulina* sp.

The results of this study indicate that liquid organic fertilizer (POC) fermented from ganyong waste for 14 days effectively supports the growth of *Spirulina* sp., as indicated by an increase in biomass of approximately fivefold the initial weight. This effectiveness is related to the maturity level of the POC, where the fermentation process allows the degradation of complex organic compounds into simpler forms that are easily assimilated by microalgae. These characteristics of mature POC align with research by Priyambodo et al. (2019) and are supported by research by Meriatna et al. (2019), which found that 11–14 days of POC fermentation produced the highest nitrogen, phosphorus, and potassium content compared to both preceding and subsequent fermentation periods. The quality of this liquid organic fertilizer (POC) from canna canna shoots was also confirmed by research by Wijihastuti et al. (2020) showed that the fertilizer met the quality specifications for liquid organic fertilizers as stipulated in the Minister of Agriculture Regulation Number 37/Permentan/SR.130/5/2010, thus optimally providing essential nutrients for the growth of *Spirulina* sp.

The absence of significant differences in specific growth rate and biomass productivity between 14 and 18 ml/L POC concentrations indicates that both treatments were within the optimal concentration range. This indicates that the nutrient requirements of *Spirulina* sp. were met at a concentration of 14 ml/L, so increasing the concentration of POC in the canna crown did not significantly affect growth responses. This nutrient saturation phenomenon aligns with several previous studies reporting that increasing the concentration of Spirulina sp. culture media does not always correlate with increased biomass (Hafidh Al et al., 2022; Lesmana et al., 2019; Nur et al., 2019; Viqram et al., 2018).

Nevertheless, the difference in the time to reach maximum growth between the two treatments indicates that nutrient concentration still influences the growth dynamics of *Spirulina* sp. At higher concentrations of canna shoot POC, the initial growth phase is slower due to the need for metabolic adaptation before cells enter the exponential growth phase. At this stage, *Spirulina* sp. adjusts to nitrogen assimilation, osmotic balance, and photosynthetic apparatus regulation, delaying cell division despite the availability of excess nutrients (Nur et al., 2019; Venkataraman, 1997). A similar pattern has been reported in *Arthrospira platensis* cultures grown in nutrient-rich or alternative media, where the lag phase or adaptation phase tends to be prolonged before optimal growth occurs (Michael et al., 2019; Russo et al., 2024).

In addition to supporting growth, canna shoot POC is also capable of producing *Spirulina* sp. biomass with a relatively high protein content, with a tendency to be greater in 14 ml/L POC media. Protein content was measured on the 11th day of culture, when the *Spirulina* sp. culture was approaching the end of the exponential phase. This condition is in line with the literature stating that the protein content of *Spirulina* sp. generally reaches its highest value in the late exponential phase (Lim et al., 2025; Maali et al., 2024). The protein percentage of around 55% is still within the commonly reported range for *Spirulina* sp., which is 55–70% of dry weight (Maddiboyina et al., 2023; Palash et al., 2025). This indicates that the canna shoot POC is able to provide essential nutrients, especially nitrogen, which supports protein synthesis (Zarrinmehr et al., 2020). The absence of significant differences between the two treatments indicates that variations in canna shoot POC concentration within the tested range did not significantly affect protein accumulation, as did the specific growth rate and biomass productivity. Overall, these results confirm the potential of canna shoot POC as an alternative nutrient source for the production of high-protein *Spirulina* sp. biomass.

Changes in Chlorophyll-a and Phycobiliprotein Pigments

The increase in chlorophyll-a content on day 8 indicates increased photosynthetic activity of Spirulina sp. during the exponential phase. The decrease in chlorophyll-a content at the end of the culture period in 14 ml/L organic fertilizer (POC) media is consistent with the culture entering the stationary phase. This also indicates the occurrence of physiological changes in the cells, which are generally associated with decreased nutrient availability (Portillo et al., 2026; Saccardo et al., 2022). Conversely, the continued increase in chlorophyll-a in 18 ml/L organic fertilizer indicates that nutrient availability at this concentration still supports pigment synthesis until the end of the culture period. However, the lack of statistically significant differences between treatments ($p > 0.05$) indicates that varying the concentration of organic fertilizer in canna shoots did not produce a significantly different physiological response, likely due to the gradual nature of organic fertilizers that provide nutrients (Shaji et al., 2021).

The pattern of phycobiliprotein pigment changes indicates the physiological response of *Spirulina* sp. to the culture environment. The increase in phycocyanin content during the exponential growth period is consistent with the role of this pigment as a major component of photosynthetic antennae that function to capture light energy (Lim et al., 2025; Maali et al., 2024). The differences in the patterns of allophycocyanin and phycoerythrin changes between the two concentrations of POC indicate that the nutrient composition of the media can selectively influence the regulation of pigment synthesis. This is in line with the results of a study by Nurjannah et al. (2025) that variations in C:N:P in the culture media significantly affect pigment biosynthesis in *Spirulina* sp., thus confirming the important role of nutrient balance in regulating microalgal pigment production (Nurjannah et al., 2025). The highest phycobiliprotein pigment content in the 14 ml/L POC media obtained on the 8th day indicates that the exponential growth phase is the optimal time for biomass harvesting if the culture objective is directed at the production of high-value pigments. These results are in line with the study by Lim et al. (2025) stated that *Spirulina* sp. phycobiliprotein production is generally maximum during the exponential growth phase.

The relatively stable phycocyanin to allophycocyanin ratio in both treatments indicates that changes in POC concentration do not significantly affect the proportion of pigments making up phycobilisomes. This stability indicates that the structure and function of the *Spirulina* sp. photosynthetic system are maintained throughout the culture period, despite variations in the dynamics of individual pigment synthesis. This finding supports the results of the statistical analysis, which showed no significant differences between treatments.

CONCLUSION

Liquid organic fertilizer produced from fermented canna plant crown waste is effective as an alternative culture medium for the growth of *Spirulina* sp. Both tested concentrations of POC, 14 and 18 mL/L, were able to support biomass growth, specific growth rate, biomass productivity, and protein accumulation of *Spirulina* sp. without statistically significant differences. The protein content of *Spirulina* sp. produced was relatively high and within the general range reported for these microalgae. The dynamics of chlorophyll-a and phycobiliprotein content were influenced by the growth phase, with the highest phycobiliprotein content obtained in the 14 mL/L POC medium on the 8th day of culture. Thus, the exponential growth phase, especially on the 8th day, is the optimal harvest time if the production goal is directed at the utilization of high-value pigments. This study confirms the potential of utilizing circular economy-based agricultural waste as a sustainable and value-added culture medium for *Spirulina* sp.

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REFERENCES

Agustini, N. W. S. (2012, 2012). *Aktivitas Antioksidan Dan Uji Toksisitas Hayati Pigmen Fikobiliprotein Dari Ekstrak Spirulina Platensis* Seminar Nasional IX Pendidikan Biologi FKIP UNS 2012, Indonesia.

AlFadhly, N. K. Z., Alhelfi, N., Altemimi, A. B., Verma, D. K., Cacciola, F., & Narayanankutty, A. (2022). Trends and Technological Advancements in the Possible Food Applications of Spirulina and Their Health Benefits: A Review. *Molecules*, *27*(17), 5584.

Amir Ali, A., & Bahareh, N. (2021). Bioactive Properties of Spirulina: A Review. *Microbial Bioactives*, *4*(1). https://doi.org/10.25163/microbbioacts.412117B0719110521

Bennett , A., & Bogorad , L. (1973). Complementary Chromatic Adaptation in A Filamentous Blue-Green Alga. *Journal of Cell Biology*, *58*(2), 419-435. https://doi.org/10.1083/jcb.58.2.419

Borowitzka, M. A. (2016). Algal Physiology and Large-Scale Outdoor Cultures of Microalgae. In M. A. Borowitzka, J. Beardall, & J. A. Raven (Eds.), *The Physiology of Microalgae* (pp. 601-652). Springer International Publishing. https://doi.org/10.1007/978-3-319-24945-2_23

Bortolini, D. G., Maciel, G. M., Fernandes, I. d. A. A., Pedro, A. C., Rubio, F. T. V., Branco, I. G., & Haminiuk, C. W. I. (2022). Functional properties of bioactive compounds from Spirulina spp.: Current status and future trends. *Food Chemistry: Molecular Sciences*, *5*, 100134. https://doi.org/https://doi.org/10.1016/j.fochms.2022.100134

Chini Zittelli, G., Lauceri, R., Faraloni, C., Silva Benavides, A. M., & Torzillo, G. (2023). Valuable pigments from microalgae: phycobiliproteins, primary carotenoids, and fucoxanthin. *Photochemical & Photobiological Sciences*, *22*(8), 1733-1789. https://doi.org/10.1007/s43630-023-00407-3

Grahl, S., Strack, M., Weinrich, R., & Mörlein, D. (2018). Consumer-Oriented Product Development: The Conceptualization of Novel Food Products Based on Spirulina (Arthrospira platensis) and Resulting Consumer Expectations. *Journal of Food Quality*, *2018*(1), 1919482. https://doi.org/https://doi.org/10.1155/2018/1919482

Hafidh Al, M., Vega, J., Dobretsov, S., & Abdala Díaz, R. T. (2022). The Effect of Medium Concentration and Nitrogen Source on the Productivity and Biochemical Composition of Arthrospira platensis. *Biology Bulletin*, *49*(2), 75-84. https://doi.org/10.1134/S1062359022020108

Hotos, G. N., & Antoniadis, T. I. (2022). The Effect of Colored and White Light on Growth and Phycobiliproteins, Chlorophyll and Carotenoids Content of the Marine Cyanobacteria Phormidium sp. and Cyanothece sp. in Batch Cultures. *Life*, *12*(6), 837. https://www.mdpi.com/2075-1729/12/6/837

Lesmana, P., Diniarti, N., & Setyono, B. D. H. (2019). The Pengaruh Penggunaan Limbah Air Budidaya ikan lele sebagai media pertumbuhan spirulina sp. *Jurnal Perikanan Unram*, *9*, 50-65. https://doi.org/10.29303/jp.v9i1.136

Lim, H. R., Khoo, K. S., & Show, P. L. (2025). Impact of nutrient deficiency and harvesting strategy on biomass and phycocyanin production in Spirulina cultures [Original Research]. *Frontiers in Bioengineering and Biotechnology*, *Volume 13 - 2025*. https://doi.org/10.3389/fbioe.2025.1546801

Lowry, O., Rosebrough, N., Farr, A. L., & Randall, R. (1951). PROTEIN MEASUREMENT WITH THE FOLIN PHENOL REAGENT. *Journal of Biological Chemistry*, *193*(1), 265-275. https://doi.org/https://doi.org/10.1016/S0021-9258(19)52451-6

Maali, A., Gheshlaghi, R., & Mahdavi, M. A. (2024). Maximizing key biochemical products of Spirulina platensis: optimal light quantities and best harvesting time☆. *OCL*, *31*, 21. https://doi.org/10.1051/ocl/2024019

Maddiboyina, B., Vanamamalai, H. K., Roy, H., Ramaiah, Gandhi, S., Kavisri, M., & Moovendhan, M. (2023). Food and drug industry applications of microalgae Spirulina platensis: A review. *Journal of Basic Microbiology*, *63*(6), 573-583. https://doi.org/https://doi.org/10.1002/jobm.202200704

Marjanović, B., Benković, M., Jurina, T., Sokač Cvetnić, T., Valinger, D., Gajdoš Kljusurić, J., & Jurinjak Tušek, A. (2024). Bioactive Compounds from Spirulina spp.—Nutritional Value, Extraction, and Application in Food Industry. *Separations*, *11*(9), 257.

Meriatna, M., Suryati, S., & Fahri, A. (2019). Pengaruh Waktu Fermentasi dan Volume Bio Aktivator EM4 (Effective Microorganisme) pada Pembuatan Pupuk Organik Cair (POC) dari Limbah Buah-Buahan. *Jurnal Teknologi Kimia Unimal*, *7*, 13. https://doi.org/10.29103/jtku.v7i1.1172

Michael, A., Kyewalyanga, M. S., & Lugomela, C. V. (2019). Biomass and nutritive value of Spirulina (Arthrospira fusiformis) cultivated in a cost-effective medium. *Annals of Microbiology*, *69*(13), 1387-1395. https://doi.org/10.1007/s13213-019-01520-4

Muys, M., González Cámara, S. J., Arnau, C., García, D., Peiro, E., Gòdia, F., Sui, Y., Vermeir, P., & Vlaeminck, S. E. (2024). Light regime, harvesting time and operation mode can optimize the productivity of nutritional protein in Chlorella and Spirulina biomass. *Algal Research*, *79*, 103443. https://doi.org/https://doi.org/10.1016/j.algal.2024.103443

Ndjouondo, G. P., Dibong, S. D., Wamba, F. O., & Taffouo, V. D. (2017). Growth, productivity and some physico-chemical factors of Spirulina platensis cultivation as influenced by nutrients change.

Nur, M. M. A., Garcia, G. M., Boelen, P., & Buma, A. G. J. (2019). Enhancement of C-phycocyanin productivity by Arthrospira platensis when growing on palm oil mill effluent in a two-stage semi-continuous cultivation mode. *Journal of Applied Phycology*, *31*(5), 2855-2867. https://doi.org/10.1007/s10811-019-01806-9

Nurjannah, I., Subroto, T., Hardianto, A., Adinisa, L., & Mochida, K. (2025). Key Nutrient Drivers for Biomass and C-Phycocyanin Production in Spirulina sp. Revealed by Media Optimization. *International Journal of Molecular Sciences*, *26*(21), 10425. https://www.mdpi.com/1422-0067/26/21/10425

Palash, M. A. U., Zahan, I., Al Solami, L. S., Islam, M. R., & Affan, M. A. (2025). Functional Properties and Applications of Spirulina (Cyanophyceae) to Animal Health Benefits: A Systemic Review. *Thalassas: An International Journal of Marine Sciences*, *41*(4), 232. https://doi.org/10.1007/s41208-025-00971-8

Pardosi, A. H., Irianto, & Mukhsin. (2014, 26-27 September 2014). Respons Tanaman Sawi terhadap Pupuk Organik Cair Limbah Sayuran pada Lahan Kering Ultisol. Seminar Nasional Lahan Suboptimal, Palembang.

Podgórska-Kryszczuk, I. (2024). Effect of Arthrospira platensis (Spirulina) Fortification on Physicochemical, Nutritional, Bioactive, Textural, and Sensory Properties of Vegan Basil Pesto. *Nutrients*, *16*(17). https://doi.org/10.3390/nu16172825

Portillo, F. V.-L., Montenegro-Herrera, C. A., Porta, H., & Martinez, A. (2026). Self-Shading effect caused by high biomass concentration increased phycocyanin accumulation in Galdieria sulphuraria strain UTEX 2919 under autotrophic conditions. *Journal of Applied Phycology*. https://doi.org/10.1007/s10811-025-03747-y

Prasadi, O. (2018). Pertumbuhan dan Biomasa Spirulina sp. dalam Media Pupuk sebagai Bahan Pangan Fungsional.

Priyambodo, G. T., Utami, K. B., & Muksid, A. (2019). Keterampilan Peternak Tentang Pembuatan Pupuk Organik Cair Dari Kotoran Kambing Di Desa Wonorejo. *Jurnal Penyuluhan Pembangunan*, *1*(2), 13-26. https://doi.org/https://doi.org/10.34145/JPPM.V1I1.58

Ritchie, R. J. (2006). Consistent Sets of Spectrophotometric Chlorophyll Equations for Acetone, Methanol and Ethanol Solvents. *Photosynthesis Research*, *89*(1), 27-41. https://doi.org/10.1007/s11120-006-9065-9

Russo, N. P., Ballotta, M., Usai, L., Torre, S., Giordano, M., Fais, G., Casula, M., Dessì, D., Nieri, P., Damergi, E., Lutzu, G. A., & Concas, A. (2024). Mixotrophic Cultivation of Arthrospira platensis (Spirulina) under Salt Stress: Effect on Biomass Composition, FAME Profile and Phycocyanin Content. *Mar Drugs*, *22*(9). https://doi.org/10.3390/md22090381

Saccardo, A., Bezzo, F., & Sforza, E. (2022). Microalgae growth in ultra-thin steady-state continuous photobioreactors: assessing self-shading effects [Original Research]. *Frontiers in Bioengineering and Biotechnology*, *Volume 10 - 2022*. https://doi.org/10.3389/fbioe.2022.977429

Scarponi, P., Fontana, L., Bertesi, F., D'Eusanio, V., Tassi, L., & Forti, L. (2024). Preliminary Evaluation of Watermelon Liquid Waste as an Alternative Substrate for Microalgae Cultivation: A Circular Economy Approach to the Production of High-Value Secondary Products by Chlorella vulgaris, Scenedesmus sp., Arthrospira platensis, and Chlamydomonas pitschmanii. *Fermentation*, *10*(11), 582. https://www.mdpi.com/2311-5637/10/11/582

Selvendran, D. (2015). Large Scale Algal Biomass (Spirulina) Production in India. In D. Das (Ed.), *Algal Biorefinery: An Integrated Approach* (pp. 151-167). Springer International Publishing. https://doi.org/10.1007/978-3-319-22813-6_7

Shaji, H., Chandran, V., & Mathew, L. (2021). Chapter 13 - Organic fertilizers as a route to controlled release of nutrients. In F. B. Lewu, T. Volova, S. Thomas, & R. K.R (Eds.), *Controlled Release Fertilizers for Sustainable Agriculture* (pp. 231-245). Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-12-819555-0.00013-3

Venkataraman, L. V. (1997). Spirulina platensis (Arthrospira): Physiology, Cell Biology and Biotechnologym, edited by Avigad Vonshak. *Journal of Applied Phycology*, *9*(3), 295-296. https://doi.org/10.1023/A:1007911009912

Viqram, V., Abidin, Z., & Mukhlis, A. (2018). Pengaruh Penambahan Pupuk Organik Guano Dengan Konsentrasi yang Berbeda Terhadap Laju Pertumbuhan Spirulina sp. *Jurnal Perikanan Unram*, *8*(2), 58-65. https://doi.org/10.29303/jp.v8i2.119

Wijihastuti, R. S., Lutfiah, A., & Noriko, N. (2020). Pengaruh Pertumbuhan Spirulina SP. terhadap Penggunaan Pupuk Organik Cair sebagai Media Tumbuh. *Jurnal Al-Azhar Indonesia Seri Sains dan Teknologi*, *5*(4). https://doi.org/10.36722/sst.v5i4.445

Zarrinmehr, M. J., Farhadian, O., Heyrati, F. P., Keramat, J., Koutra, E., Kornaros, M., & Daneshvar, E. (2020). Effect of nitrogen concentration on the growth rate and biochemical composition of the microalga, Isochrysis galbana. *Egyptian Journal of Aquatic Research*, *46*(2), 153-158. https://doi.org/https://doi.org/10.1016/j.ejar.2019.11.003

Zhu, B., Shen, H., Li, Y., Liu, Q., Jin, G., Han, J., Zhao, Y., & Pan, K. (2020). Large-Scale Cultivation of Spirulina for Biological CO2 Mitigation in Open Raceway Ponds Using Purified CO2 From a Coal Chemical Flue Gas [Original Research]. *Frontiers in Bioengineering and Biotechnology*, *Volume 7 - 2019*. https://doi.org/10.3389/fbioe.2019.00441