Research Article

Enhancing the Photosynthetic Efficiency, Stomatal Conductance and Nutrient Uptake in Wax Apple (*Syzygium samarangense*) Seedlings Using *Sargassum polycyctum* and *Spirulina platensis* Extract

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Abstract | Algal extracts are emerging as a promising, sustainable solution for enhancing plant growth and physiological performance. This research investigated the biostimulatory impacts of algae extracts of *Spirulina platensis* and *Sargassum polycystum* on the photosynthetic efficiency and nutrient uptake in wax apple seedlings. Uniform size of wax apple seedlings was foliar sprayed weekly for eight weeks, using aqueous algal extract at various concentration of *S. platensis* extract; T0 (0.0%), T1 (2.5%), T2 (5.0%), T3 (10.0%) and various concentration of *S. polycystum* extract; T4 (2.5%), T5 (5.0%), T6 (10.0%) as well as T7, 5.0% (1:1) of mixed extract. There were five replicates of each treatment, which was conducted using a Randomized Complete Block Design (RCBD). The results demonstrated distinct increase in chlorophyll *a*, chlorophyll *b* and carotenoid in T3 (10.0% *S. platensis* extract) treatment with 59.34%, 50.98% and 11.27% respectively over control, resulting in the highest total chlorophyll. While T6 (10.0% *S. polycystum* extract) gave the greatest SPAD reading with 83.65% increase. At the meantime, the T3 also showed the significant increase by 6.84% and12.38% respectively in Fo and Fm value. Fv/Fm and Fv/Fo ratios were also significantly enhanced by the similar treatment with values of 0.81 and 2.85, respectively. An increase in stomatal conductance was seen as a result of algal extract application, specifically in T3 (55.96%), followed by T5 (5.0% *S. polycystum* extract) (52.43%) and T6 (50.74%), respectively. Additionally, algal extracts were found to enhance the nutrient uptake in wax apple seedlings. T3 signified the most improved uptake of N, P, K, Cu, Fe and Mn by 56.03%, 130.0%, 106.83%, 75.0%, 117.78% and 145.0% accordingly, compared to control. In contrast, the greatest uptake of Ca and Zn can be seen in T6 treatment with 104.55% and 66.67% respectively over control. However, both T3 and T6 exhibited similar influence in Mg uptake. These findings provide further evidence that extract derived from *S. platensis* and *S. polycystum* are efficacious in enhancing physiological parameters critical for plant growth. These extracts enhance photosynthetic efficiency, nutrient absorption, and stomatal function, providing a sustainable and environmentally benign method for enhancing the production of high-value crops such as wax apple, hence improving agricultural output and environmental resilience.

Received | January 23, 2025; **Accepted** | February 16, 2025; **Published** | April 30, 2025
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Citation | Tajol, M.T.F.M., M.M. Khandaker, N.E.M. Shaari and N.H. Mahmod. 2025. Enhancing the photosynthetic efficiency, stomatal conductance and nutrient uptake in wax apple (*Syzygium samarangense*) seedlings using *sargassum polycyctum and spirulina platensis* extract. *Sarhad Journal of Agriculture,* 41(2): 660-673.
DOI | https://dx.doi.org/10.17582/journal.sja/2025/41.2.660.673
Keywords | Algal extracts, *Sargassum polycyctum*, *Spirulina platensis*, Wax apple

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Introduction

The wax apple, scientifically known as *Syzygium samarangense* ([Blume] Merrill and L.M. Perry), is a tropical fruit that is prized for its shiny, smooth exterior and distinctive bell form. (Tuladhar and Nii, 2017). This plant is classified under the eudicot family Myrtaceae and is referred to by several names, including Java apple, rose apple, and wax jambu (Palanisamy *et al*., 2011; Sonawane, 2018; Lim, 2012). Wax apple holds significant economic and nutritional value in Southeast Asia. being rich in water content and vitamin C, it serves as an excellent source of hydration, particularly benefiting skin health (Prommaouan *et al*., 2022). Additionally, the fruit is abundant in anthocyanins, which are effective in neutralizing harmful free radicals, alongside phenolic compounds, flavonoids, and antioxidants (Khamchan *et al*., 2018; Shen *et al*., 2012). Notably, the flavonoids extracted from wax apple exhibit properties such as antihyperglycemic, spasmolytic, and immunomodulatory effects (Khandaker and Boyce, 2016; Resurreccion-Magno *et al*., 2005).

Research also indicates that wax apple offers protective benefits against hypercholesterolemia and its related complications. Specifically, it has been shown to improve lipid profiles, mitigate oxidative stress, and reduce vascular and hepatic damage in hypercholesterolemic animal models (Prommaouan *et al*., 2022). In addition to its health benefits, the wax apple is highly appreciated for its balanced sweetness and crisp, juicy texture, which surpasses that of conventional apples. Its mild and refreshing flavor profile makes it a popular and hydrating fruit, supporting extensive cultivation in tropical regions such as Malaysia, Thailand, Indonesia, Taiwan, and the Philippines (Shü *et al*., 2011). Despite its nutritional and economic potential, wax apple (*Syzygium samarangense*) cultivation faces numerous challenges, including susceptibility to climatic extremes, soil salinity, pest pressures and market fluctuations, all of which hinder sustainable production and fruit quality (APAARI, 2014). To address these issues, the use of mineral fertilizers over the last century has played a pivotal role to substantial yield improvements in agricultural intensification output and quality (Choudhary *et al*., 2021; Syed *et al*., 2021). Recently, global fertilizer production reached 207.7 million metric tons with East Asia emerged as the leading region, contributing over 31% of global production capacity, which are key contributors in nitrogen and phosphate fertilizers (FAO, 2019).

The extensive dependence on chemical fertilizers in contemporary agriculture has generated much apprehension about soil health, environmental sustainability, and food safety. The extended application of these fertilizers, especially nitrogen-based and NPK formulations, correlates with soil acidification, nutrient imbalances, and disruption of microbial ecosystems, ultimately reducing crop nutritional quality (Syed *et al*., 2021; Raza *et al*., 2020). The depletion of air and soil quality is accelerated by certain fertilizers that contain heavy metals. These effects pose substantial long-term risks to environmental integrity and human health (Das *et al*., 2023; Levarity and Gustave, 2024; Ritchie, 2021). In light of these challenges, there is a growing need to adopt alternative approaches that enhance agricultural productivity while mitigating environmental harm (Levarity and Gustave, 2024). Among these alternatives, particularly those derived from seaweed, biostimulants offer a promising solution. Seaweed-based biostimulants are rich in bioactive compounds, particularly phytohormones, polysaccharides, and essential minerals, which enhance plant resilience to biotic and abiotic stress (Solano Porras *et al*., 2023). They achieve this by improving water-use efficiency and nutrient absorption, thereby supporting root and shoot development, improving overall plant health and yield, and mitigating the ecological consequences attributed to the overuse of chemical fertilizers (Halshoy and Sadik, 2024).

Integrating seaweed-derived biostimulants into agricultural practices can help reduce dependency on agrochemicals, enhance fruit quality, and promote soil quality, thereby contributing to more sustainable and productive farming systems. Among the promising biostimulants, the brown macroalga *S. polycystum* and the cyanobacterium *S. platensis* and out due to their exceptional potential as natural plant growth enhancers (Abd Tahar *et al*., 2024; Ammar *et al*., 2022). *S. polycystum* is notably abundant in polysaccharides, phenolic compounds, and essential minerals, which together facilitate improved nutrient absorption, enhanced photosynthetic efficiency, and increased stress resilience in plants (Abd Tahar *et al*., 2024). Its application has demonstrated significant benefits in various crops. Research has demonstrated that applying *Sargassum* extracts to rice plants through the leaves improves growth and yield. This is because the extracts increase nutrient availability and plant metabolic processes (Mohammed *et al*., 2023). Similarly, its use in crops such as sunflower and tomato has resulted in notable improvements in physiological traits, including chlorophyll content, enzymatic activity, and nutrient absorption (Fatimah and Daud, 2018).

Spirulina platensis, a cyanobacterium celebrated for its elevated protein content and diverse bioactive components, including vitamins, minerals, and antioxidants, has shown considerable promise in agriculture. Its use is linked to increased root elongation, shoot development, and biomass production, driven by enhanced physiological processes like nutrient absorption and chlorophyll synthesis. (Shaari *et al*., 2023). Research has further highlighted its capacity to enhance the growth and productivity of economically important crops, such as tomatoes, through its nutrient-dense composition and growth-promoting properties (Mostafa *et al*., 2024). These findings emphasize the potential of *S. platensis* as a sustainable biostimulant capable of lowering the need for artificial fertilizers while simultaneously increasing plant health and yield.

Despite comprehensive studies on the impact of algae-based biostimulants on typical crops, their utilization in high-value fruit crops like wax apple remains limited. Most studies to date have concentrated on morphological and growth responses in plants treated with biostimulants, leaving a critical gap in understanding their influence on physiological parameters and nutrient dynamics. Physiological indicators, such as chlorophyll content, photosynthetic efficiency and stomata behaviour are crucial for evaluating plant health and productivity but have not been thoroughly examined in wax apple cultivation. Likewise, the function of biostimulants in improving the absorption and distribution of essential nutrients in wax apple seedlings has been predominantly unexplored. Therefore, this study investigated the effects of *S. polycystum* and *S. platensis* biostimulants on the physiological parameters and nutrient profiles of wax apple seedlings, to promote sustainable agriculture practices and offer new perspectives on the possibilities of algae-derived products in the cultivation of high-value fruit crops.

Material and methods

Algal collection

S. polycystum was hand-harvested during low tide from Blue Lagoon, Port Dickson, Negeri Sembilan, Malaysia (2°24′56.5″ N, 101°51′17.5″ E). The algae were rinsed with seawater to remove impurities and stored on ice, later transported to the lab for morphological identification according to (Shaari *et al*., 2023). *S. platensis* was obtained from Algaeliving SDN. BHD. and cultured in Zarrouk's medium at 25°C under fluorescent light (1020 lux) with aeration from filtered air. The pH was altered using 1 M NaOH or 1 M HCl. By measuring optical density at 730 nm, the growth of *S. platensis* was monitored. After 30 days, the biomass was collected by centrifugation, sun-dried for four hours, and stored at -18°C.

Algae extraction

The *Sargassum* and *Spirulina* samples were air-dried at 20°C for a period of two days. A 50g of desiccated biomasses were added with 500 mL of distilled water and heated at 70°C for 2h, following a modified method from Pise and Sabale (2010). The liquid was subsequently purified through vacuum filtration, after centrifugation at 4000 rpm for 10 minutes. The pH and colour of the final extract were recorded for extract characterization. This 100% concentrated algal extract solution was stored and diluted as needed for experiments.

Experimental design and plantation

The experiment was conducted at the shade house of the Faculty of Bioresources and Food Industry, Universiti Sultan Zainal Abidin (UniSZA), Besut Campus, Terengganu, Malaysia. Wax apple (*Syzygium samarangense*) seedlings were propagated via air layering. After two months, forty uniform-sized cuttings were selected and transplanted into polybags filled with soil collected from an agricultural farm in Jerteh, Terengganu. The soil was initially air-dried, then sieved using a 2 mm mesh, and thereafter analysed for essential qualities.: pH (6.2), nitrogen (0.15%), carbon (1.50%), phosphorus (21 mg/kg), and cation exchange capacity (CEC, 10.8 cmol(+)/kg). Base cation levels were measured as 2.2 cmol (+)/kg potassium, 1.50 cmol (+)/kg calcium, and 1.05 cmol (+)/kg magnesium. The soil texture, comprising 35.8% coarse sand, 10.1% fine sand, 40.0% clay, and 12.5% silt. confirmed its suitability for plant growth.

After a one-month acclimatization period, the seedlings were subjected to weekly foliar treatments of algal extracts for two months. The treatments included 0.0% (control), 2.5%, 5.0%, and 10.0% of *S. platensis* and *S. polycystum* extracts, as well as a combined treatment of 5.0% of each extract in a 1:1 ratio. Each application involved the manual spraying of 100 mL extract onto the foliage of each seedling. Untreated seedlings served as the control group. The experiment was structured as a Randomized Complete Block Design (RCBD) featuring five replicates for each treatment. Data was collected and analysed to assess the impact of algal extracts on plant physiological characteristics, nutrient absorption, and growth metrics.

Table 1: *The design of experiments to examine the effects of S. polycystum and S. platensis extracts on chlorophyll content, chlorophyll fluorescence, stomatal conductance and nutrient uptake of wax apple seedlings.*

Treatment	Description
T0	0.0% extracts
T1	2.5% *S. platensis* extracts
T2	5.0% *S. platensis* extracts
T3	10.0% *S. platensis* extracts
T4	2.5% *S. polycystum* extracts
T5	5.0% *S. polycystum* extracts
T6	10.0% *S. polycystum* extracts
T7	5.0% *S. platensis* + *S. polycystum* extracts

Chlorophyll a, b, Carotenoid and SPAD (Soil Plant Analysis Development)

Utilizing 80% acetone as the extraction medium, the chlorophyll content was determined in accordance with the methodology that was reported by Lichtenthaler and Wellburn (1983). In order to separate the supernatant from the residual leaf material, fresh leaf samples weighing 200 mg were carefully weighed, then crushed in 4 mL of 80% acetone, and last filtered and centrifuged. The volume of the extract was adjusted to a total of 10 mL by adding 80% acetone to the initial amount. Readings of absorbance were obtained at wavelengths of 470, 645, and 663 nm using UV-visible spectrophotometer (Shimadzu UV mini-1240, Kyoto, Japan), and the amounts of chlorophyll were determined by employing particular formula;

$$Chl\ a = [\,12.7(0.\,D\ 663) - 2.69(0.\,D\ 645)]$$

$$Chl\ b = [\,22.9(0.\,D\ 645)] - 4.68(0.\,D\ 663)]$$

$$Total\ Chlorophyll = Chl\ a + Chl\ b$$

$$Carotenoids\ Content = (1000A470 - 3.27(Chl\ a) - 104\,(Chl\ b)/229$$

Additionally, SPAD reading was recorded using a handheld SPAD 502-Plus Chlorophyll meter.

Chlorophyll Fluorescence

Chlorophyll fluorescence was evaluated with a Handy PEA meter (Hansatech Instrument, United Kingdom), in accordance with the methodology described by Padhi *et al*. (2021). A leaf clip was attached to the selected leaf, ensuring it completely covered the measurement area. The shutter of the clip was closed to allow the leaf to undergo dark adaptation for 15 minutes. Once the adaptation period was completed, the shutter was opened to enable the sensor to record the fluorescence emitted by the leaf. Parameters; Fm (maximum fluorescence under continuous light intensity) and Fv (variable fluorescence representing the maximum capacity for photochemical quenching) were recorded to calculate the Quantum Yield (Fv/Fm = maximum quantum efficiency of Photosystem II) in wax apple treated with algal extracts.

Stomatal conductance

A portable porometer (Decagon SC-1 Leaf Porometer), was used to determine the stomatal conductance, or the rate of gas exchange, in wax apple leaves. Measurements were taken from fully mature leaves in each treatment group, under controlled conditions between 9:00 and 11:00 a.m., to reduce midday fluctuations and ensure consistency. Prior to each measurement session, the porometer was calibrated following the manufacturer's instructions. Leaves were secured in the porometer chamber, and measurements were recorded once stable values were achieved, indicating equilibrium in gas exchange. Results were expressed in mmol $m^{-2} s^{-1}$.

Nutrient uptake analysis

Leaf samples were meticulously rinsed with distilled water to eliminate surface impurities and subsequently dried in an oven at 70°C until a stable weight was attained. The desiccated samples were meticulously pulverized with a laboratory mill and preserved in hermetically sealed containers for analysis. Kjeldahl method (Yeoh and Wee, 1994) was employed to measure nitrogen (N) content in leaf sample. Concentrated sulfuric acid (H_2SO_4) was used to digest precisely 0.5g of crushed leaf tissue, with addition of a catalyst under controlled heating until a clear solution was obtained. The digest was neutralized and distilled to determine total N. For other macronutrients (P, K, Ca and Mg) and micronutrients (Fe, Cu, Zn, and Mn), Sample preparation was conducted in accordance with Baumgärtel *et al*. (2023). Powdered leaf sample (0.2 mg) was digested using 10 mL HNO_3 in microwave digesting system (Anton Paar MULTIVAWE 3000, Graz, Austria). The digested samples were filtered, diluted with deionized water, and analyzed using Inductively Coupled ICP-OES (Bruker Aurora M90 ICPMS, Billerica, MA, USA) to quantify elemental concentrations with high precision.

Statistical Analysis

The experiment employed a Randomized Complete Block Design (RCBD), with five replications of each treatment. Data analysis was conducted using SPSS-17 statistical software, employing the two-way ANOVA method to ascertain significant differences among the parameters. Tukey's HSD test was utilized to evaluate the effects of varying doses of algal extracts on the assessed parameters, with significance established at p = 0.05.

Results

Physiological parameters

Chlorophyll a, b, carotenoid and SPAD

The results demonstrated a concentration-dependent enhancement in chlorophyll *a* (Chl *a*), chlorophyll *b* (Chl *b*), carotenoid and SPAD values in response to algal extract treatments. The greatest Chl *a* content was recorded in the T3 treatment, representing a 59.34% increase over T0. Similarly, the T6 and T7 treatments led to significant increases in Chl *a*, with enhancements of 52.72% and 41.05%, respectively, compared to the T0 (Table 2). No notable differences were detected among the remaining treatments. A comparable trend was noted for Chl *b*, where the T3 treatment showed the highest content, reflecting a 50.89% increase over the T0. Significant increases in Chl *b* were also recorded in the T4 (39.07%), T6 (48.74%) and T7 (35.84%) treatments over the T0. There were no statistically significant variations in Chl *b* levels in other treatments that were administered. Carotenoid levels followed a comparable pattern, with the highest accumulation observed in the T6 treatment, which resulted in an 83.65% increase over the T0. The T4 and T3 treatments also significantly enhanced carotenoid content by 70.44% and 56.60% respectively compared to T0. Furthermore, the remaining treatments did not show in any significant variations in the levels of carotenoid. These biochemical differences are further illustrated by the accompanying image (Figure 1), where variations in leaf coloration clearly reflect the enhanced pigment accumulation observed in the treated samples. This concentration-dependent response underscores the potential of algal extracts to enhance pigment accumulation in plants, with notable effects observed at higher treatment concentrations. This concentration-dependent response underscores the potential of algal extracts to enhance pigment accumulation in plants, with notable effects observed at higher treatment concentrations.

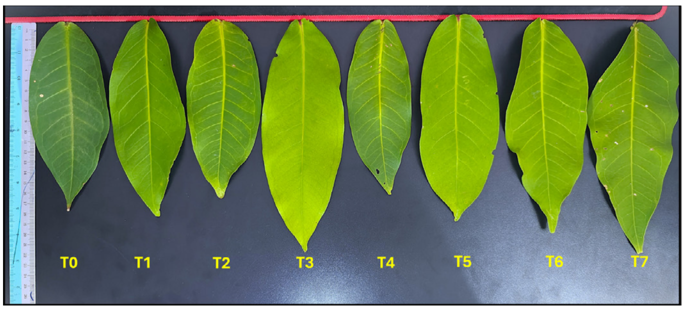

Figure 1: *Images of the wax apple leaves after exposure to S. platensis and S. polycystum extracts at varying concentrations. The details of the treatments (T0–T7) are provided in Table 1.*

The SPAD readings revealed significant differences among treatments, indicating varying effects on

Table 2: *The chlorophyll content and SPAD reading of wax apple seedlings after algal extract treatment.*

Treatment	Chl a	Chl b	Total Chl	Carotenoid	SPAD
T0	5.14±0.27c	2.79±0.12c	7.93±0.39cd	1.59±0.10c	44.55±0.83c
T1	4.90±0.40c	2.57±0.16c	7.46±0.56d	1.35±0.11c	46.75±0.28abc
T2	5.49±0.29bc	2.76±0.12c	8.24±0.41bcd	1.49±0.10c	46.02±1.31bc
T3	8.19±0.28a	4.21±0.09a	12.40±0.37a	2.49±0.09a	49.57±2.91a
T4	6.85±0.28abc	3.88±0.18ab	10.74±0.40abc	2.71±0.26a	45.97±1.94bc
T5	6.65±0.63abc	3.35±0.35bc	10.00±0.98abcd	1.87±0.27b	46.02±1.05bc
T6	7.85±0.95a	4.15±0.27ab	11.99±1.22a	2.92±0.08a	48.12±0.45ab
T7	7.25±0.51ab	3.79±0.24ab	11.04±0.74ab	2.27±0.18ab	47.6±0.46abc

Values (n = 5) denoted by identical letters exhibited no significant difference at $p < 0.05$. The standard errors represent the variability among the five replicates. Treatments are described more in detail in Table 1.

chlorophyll content and photosynthetic potential. Treatment T3 demonstrated the highest SPAD value with 11.27% increase over the control (Table 2). This suggests that T3 effectively enhanced chlorophyll retention, likely due to its nutrient-rich composition or bioactive compounds. Another treatment that gives significant effects on SPAD reading was T6 marking a 7.99% improvement over T0. These results indicate that T3 and T6 were the most effective treatments in boosting photosynthetic efficiency. Other treatments, such as T7, T5, and T4, exhibited SPAD enhancement by 6.83%, 3.30%, and 3.19% over the T0 respectively as shown in Table 2. Although these values were moderately higher than T0, they did not show significant differences among themselves. These findings highlight the efficacy of algal extract treatments, especially T3 and T6 in improving crop health and productivity through optimized chlorophyll levels.

Chlorophyll fluorescence

The results highlight the significant influence of algal extract treatments on key photosynthetic parameters, including initial fluorescence (Fo), maximum fluorescence (Fm), and the maximum quantum efficiency of photosystem II (Fv/Fm), reflecting enhanced photosynthetic performance and structural integrity of the photosynthetic apparatus across treatments. The Fo which indicates the minimum level of chlorophyll fluorescence when all reaction centres are open, significantly greater than control plant. The highest Fo value was recorded in T3, reaching 6.84% increase compared to T0 (Figure 2a). Other treatments such as T2, T5, and T6 showed elevated Fo values of 5.10%, 4.42%, and 5.71% increase respectively over the T0. These increases suggest that the treatments enhanced the structural and functional integrity of the photosynthetic apparatus, with T3 demonstrating the most pronounced effect, likely due to optimal bioactive compound composition.

The Fm reading, which indicates the peak chlorophyll fluorescence when all reaction centres are closed, also showed significant variations among treatments, highlighting differences in the potential photosynthetic efficiency of the plants. (Figure 2b) shows that T3 exhibited the highest Fm value with substantial 12.83% increase over T0. T2 and T6 also showed elevated Fm values of 9.21% and 9.50% increase accordingly. Moderate improvements were noted in T1, T4, and T5, with Fm values ranging from 6.11% to 8.27% increase over the T0. Based on these findings, it appears that the algal extract treatments were successful in increasing the maximum photochemical capacity of the photosystems, with T3 exhibiting the most significant improvement.

The Fv/Fm ratio, representing the maximum quantum efficiency of photosystem II (PSII), was positively increased in agal extract treatments, indicating the impact of algal extracts on photosynthetic performance. T3 demonstrated the highest Fv/Fm value of 0.81, marking a 5.63% improvement over the control as shown in Figure 2(c). Treatments T2 and T6 also exhibited substantial increases, with enhancements of 4.23% each compared to T0. Moderate improvements were recorded for T5 (2.82%) and T7 (2.82%), while T1 and T4 showed smaller increases of 1.41%. These results underscore those treatments, particularly T3, significantly improved the photochemical efficiency of PSII, indicating the beneficial effects of algal extracts on the plants' photosynthetic potential.

The Fv/Fo ratio reflects the photosystem II efficiency in the experiment. Figure 2d exhibits notable

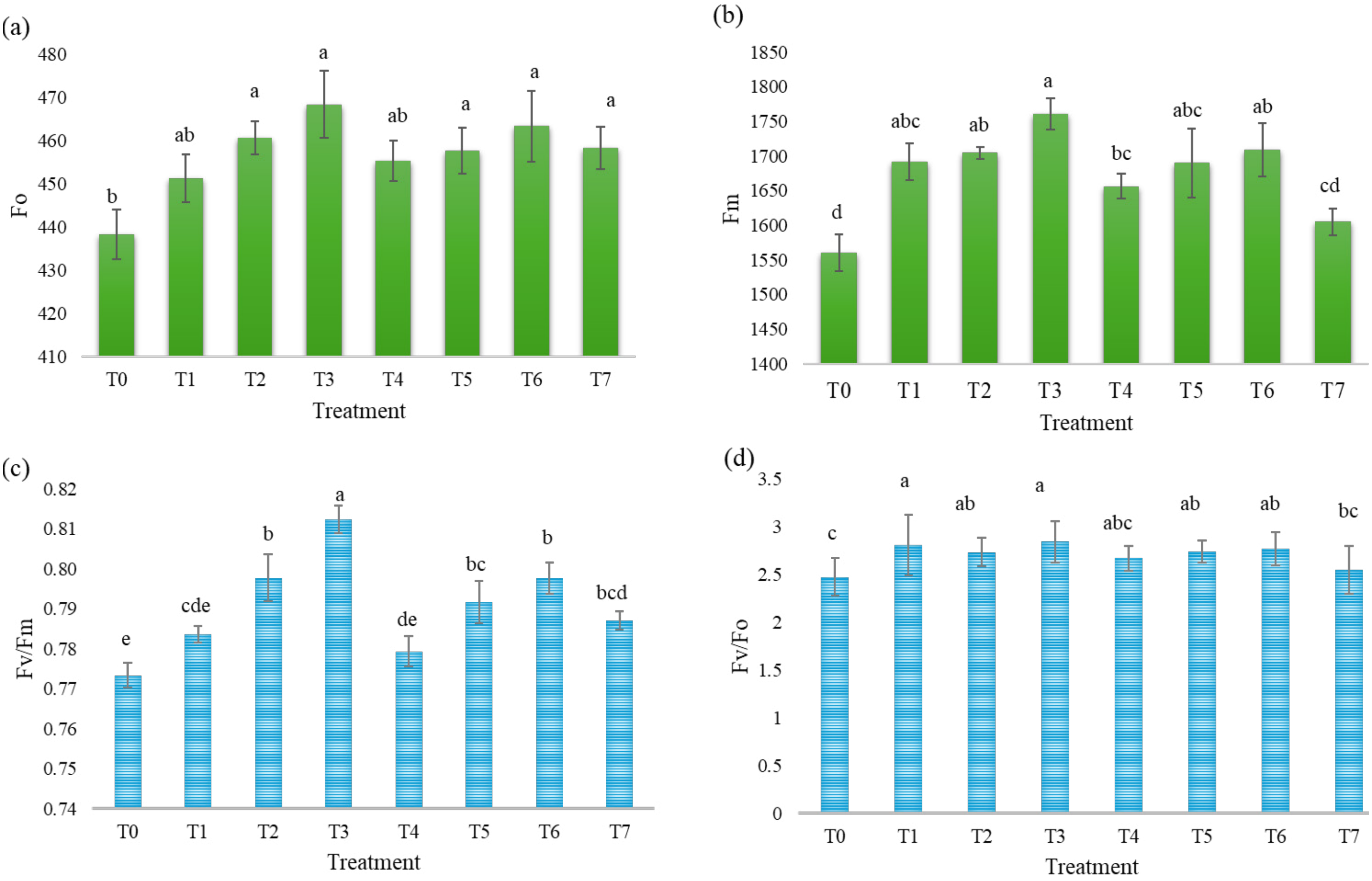

Figure 2: *The chlorophyll fluorescent analysis of wax apple's leaf after treatment of algal extracts, (a) Fo, (b) Fm, (c) Fv/Fm and (d) Fv/Fo. Values (n = 5) denoted by identical letters exhibited no significant difference at p < 0.05. Error bars denote the standard errors of five replicates.*

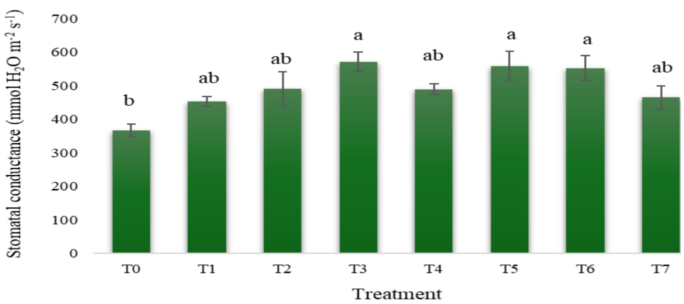

Figure 3: *The stomatal conductance of leaf of wax apple as affected by different concentrations of algal extracts. Values (n = 5) denoted by identical letters exhibited no significant difference at p < 0.05. Error bars denote the standard errors of five replicates.*

effects of different concentration of algal extracts onto wax apple's leaf. T3 recorded the greatest value of Fv/Fo (2.85) over control. This suggests that 10.0% of *S. platensis* extract significantly improved photosynthetic efficiency. T1 and T2 also showed positive effects, with Fv/Fo ratios of 2.81 and 2.74, respectively. Increasing concentration of *S. polycystum* extracts also significantly increased the Fv/Fo value with 2.74 and 2.77 respectively in T4 and T5 over the T0. T7 showed slight increase of Fv/Fo over control with no discernible different.

Stomatal conductance

Figure 3 demonstrates the stomatal conductance of wax apple's leaf after algal extract treatments. The T3 treatment recorded the highest stomatal conductance value of 55.96% increase compared to the T0. Similarly, treatments T5 and T6 exhibited marked improvements, with increases of 52.43% and 50.74% over T0, respectively. Moderate enhancements were observed in T2 (33.91%), T4 (33.49%), and T7 (26.89%) (Figure 3) over the T0. These results suggest that the application of algal extracts positively influenced stomatal behaviour, likely improving the balance between photosynthetic carbon assimilation and water-use efficiency. The significantly higher stomatal conductance in T3 indicates its superior capacity to optimize gas exchange, potentially contributing to better overall plant growth and productivity.

Nutrient uptake

The finding reveals that the different algal extracts and

Table 3: *The levels of nutrient contents (g kg^{-1}) of leaf of wax apple seedlings as affected by different concentration of algal extracts.*

Treatment	N	P	K	Ca	Mg	Cu	Zn	Fe	Mn
T0	11.94±0.04g	0.20±0.04e	4.83±0.01g	3.96±0.22g	0.74±0.04g	0.40±0.07d	0.21±0.01d	0.45±0.02d	0.20±0.01d
T1	12.63±0.07f	0.25±0.04e	4.85±0.01g	6.29±0.23e	1.02±0.04f	0.53±0.06bc	0.26±0.01b	0.48±0.01cd	0.31±0.05bc
T2	17.96±0.11b	0.33±0.07bc	6.93±0.14d	6.14±0.22e	1.12±0.08e	0.65±0.05ab	0.23±0.01c	0.49±0.02bcd	0.38±0.02ab
T3	18.63±0.07a	0.46±0.07a	9.99±0.15a	7.71±0.14b	1.51±0.17a	0.70±0.12a	0.33±0.01a	0.98±0.06a	0.49±0.01a
T4	14.79±0.11d	0.23±0.19d	6.62±0.09e	5.29±0.28f	1.25±0.18c	0.48±0.01cd	0.28±0.01ab	0.48±0.01cd	0.23±0.02cd
T5	15.25±0.19c	0.30±0.11c	7.53±0.08c	6.98±0.13d	1.16±0.15d	0.56±0.03bc	0.29±0.02ab	0.51±0.02bc	0.28±0.02bc
T6	15.38±0.07c	0.36±0.11b	8.84±0.08b	8.10±0.15a	1.54±0.11a	0.61±0.05ab	0.35±0.01a	0.84±0.05ab	0.45±0.04ab
T7	14.21±0.11e	0.33±0.07bc	5.97±0.07f	7.30±0.21c	1.28±0.07b	0.55±0.07bc	0.31±0.02ab	0.58±0.02bc	0.30±0.02bc

Values (n = 5) denoted by identical letters exhibited no significant difference at $p < 0.05$. The standard errors represent the variability among the five replicates. Treatments are detailed in Table 1.

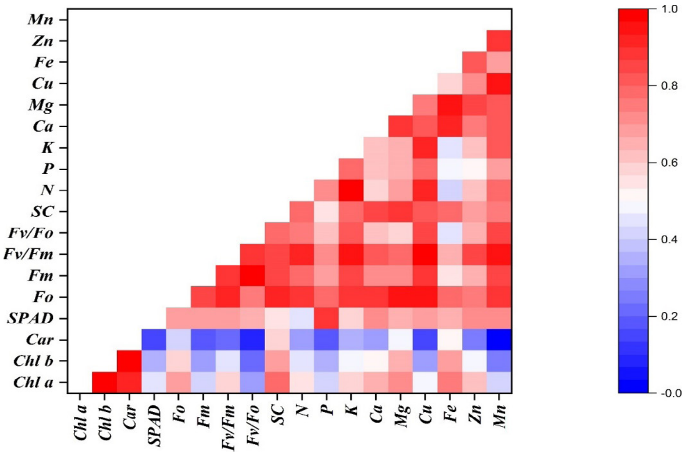

Figure 4: *Pearson's correlation among the evaluated parameters of wax apple seedlings following treatments with S. platensis and S. polycystum extracts at varying doses. Chl a = chlorophyll a, Chl b = chlorophyll b, Car = carotenoid, SPAD = Soil-Plant Analysis Development, Fo = minimum fluorescence yield, Fm = maximum fluorescence yield, Fv/Fm = maximum efficiency of photosystem II (PSII), Fv/Fo = maximum quantum yield of PSII, SC = stomatal conductance, N = nitrogen, P = phosphorus, K = potassium, Ca = calcium, Mg = magnesium, Cu = copper, Fe = iron, Zn = zinc and Mn = manganese.*

their various concentration significantly influenced the macro-micronutrients content in leaf of wax apple. As tabulated in Table 3, treatment T3 showed the most pronounced effects, with notable increase in N, P, and K surpassing control by 56.03%, 130.0% and 106.83% respectively. While T6 showed the greatest Ca content in wax apple's leaf by 104.55% increase in comparison to control. However, both T3 and T6 signified the same effects on Mg content with 104.05% and 108.11% respectively. According to Table 3, T3 treatment demonstrated a substantial rise in micronutrients, with increases of 75.0%, 117.78%, and 145.0% in Cu, Fe, and Mn, respectively over control. This signifies that T3 exerted the most pronounced influence on micronutrient accumulation, implying that the administered treatment augments the plant's capacity to absorb and retain essential elements. While Zn was most recorded in T6 with 66.67% increase accordingly compared to control, followed by T3 (57.14%), T7 (47.62%), T5 (38.01%) and T4 (33.33%).

Based on the findings, other treatments also had a substantial impact on the level of macronutrients that wax apple seedlings taken up, and this impact was positively correlated with the concentration of algal extract. Nevertheless, these findings suggest that T3 and T6 had a substantial and favourable impact on the accumulation of nutrients. This may be the result of the particular formulation of the treatments, which either improves the efficiency with which wax apple seedlings utilize nutrients or increases the amount of nutrients that are taken in by the plants.

Pearson's correlation

Figure 4 reveales the Pearson correlation matrix of physiological, biochemical, and nutrient parameters in algal extract treated-wax apple seedlings. Strong positive correlations were observed between chlorophyll content (Chl *a*, Chl *b*), carotenoids (Car), SPAD values, and chlorophyll fluorescence parameters (Fv/Fo, Fv/Fm), indicating a close relationship between pigment content and photosynthetic performance. Nutrients including K, P, Mg, and Ca exhibited favourable correlations with micronutrients such as Mn, Zn, Fe, and Cu, highlighting their synergistic functions in plant metabolic processes. Conversely, negative correlations were observed between certain micronutrients like Mn, Zn and chlorophyll content, suggesting possible inhibitory effects at higher concentrations. The correlations presented provide a major viewpoint on the physiological and biochemical interactions that influence plant growth. They highlight critical traits and nutrient dynamics that can be leveraged to improve overall plant productivity and practices related to nutrient management.

Discussion

Chlorophyll content

The concentration-dependent increases in chlorophyll *a* (Chl *a*), chlorophyll *b* (Chl *b*), and carotenoid levels in response to algal extract treatments demonstrate the efficiency of algal extracts in enhancing photosynthetic pigment accumulation in wax apple trees. The results indicates that T3, T5, and T7 treatments significantly increased Chl *a*, Chl *b*, carotenoid levels, and SPAD readings, suggesting that higher concentrations of *S. platensis* and *S. polycystum* can boost the photosynthetic potential of wax apple seedlings. Mutale-Joan *et al.* (2020) conducted a study showing that the use of microalgae extract consortia significantly boosted chlorophyll content, with some species experiencing up to a 92% increase in chlorophyll b compared to control plants. Applying protein-rich *S. platensis* extracts externally to red beets improved their nutrient content, hypocotyl development, and chlorophyll levels (Mógor *et al*., 2018). The extract of *Chlorella vulgaris* at 5.0% was observed to improve the overall level of chlorophyll, carotenoids, polyphenols, and flavonoids in plant tissues, consequently increasing growth and secondary metabolites (Kusvuran, 2021). The chlorophyll content of fenugreek plants was also substantially improved after the application of *Sargassum ilicifolium* and *Ulva lactuca* extracts (Prisa *et al*., 2024). (Jamaludin *et al.* (2020) also reported that growth promoting chemicals like hydrogen peroxide (H_2O_2) improved the chlorophyll content of *Ficus deltoidea* plants. Photosynthesis relies on this fundamental pigment's ability to absorb light. According to Li *et al* (2023), improved photosynthetic efficiency is a direct result of a higher chlorophyll content

Algal extracts can enhance photosynthetic capacity in plants by boosting pigment production through the provision of essential nutrients and growth-promoting substances (Michalak *et al*., 2016). The mechanisms underlying these increases are complex, encompassing biochemical and physiological processes that result in enhanced plant development and productivity. Nutrients that are necessary for pigment production can be found in abundance in algal extracts. At the time of chlorophyll synthesis, the availability of N and Mg are crucial elements. Algal extracts offer forms of N and Mg that are readily available to the plant, which in turn encourages the development of healthy leaves and supports optimal chlorophyll production (Gharib *et al*., 2024; Michalak *et al*., 2016). According to Mutale-Joan *et al.* (2020), the increase in chlorophyll production was completely associated with the increased uptake of N and K by the roots of the plant. Spirulina supplementation has shown the enhancement of nutrient absorption in plants, which is crucial for their overall growth and development. This is supported by findings that indicate increased chlorophyll content and photosynthetic activity in *Solanum lycopersicum* L. and *Lupinus luteus* treated with 10% Spirulina extracts (Mostafa *et al*., 2024; Shedeed *et al*., 2022). Parmar *et al.* (2023) highlighted that microalgae are rich in micronutrients such as Fe and Mn that play a significant role in a variety of enzymatic events in the process of chlorophyll synthesis and the overall metabolism of plants. The presence of bioactive chemicals in algal extracts is another factor that contributes to the growth of the plant. Phytohormones like auxins, cytokinins, and gibberellins found in algal extracts stimulate cell division and elongation, leading to larger leaf areas and increased chlorophyll content (Michalak *et al*., 2016).

Chlorophyll fluorescence and stomatal conductance

The current study demonstrates that algal extracts from *S. platensis* and *S. polycystum* significantly influenced the chlorophyll fluorescence parameters Fo (minimum fluorescence), Fm (maximum fluorescence), and the ratio Fv/Fm (variable fluorescence ratio), which are essential indicators of photosynthetic efficiency and health of wax apple seedlings. T3 and T6 in Figure 2(a-c), were observed to give higher reading of F0, Fm and Fv/Fm compared to control and other treatments. The utilization of algal extracts can augment the physiological conditions of plants, resulting in enhanced values of fluorescence parameters. Studies have shown that when plants are treated with algal extracts, there is often an increase in Fm due to enhanced light absorption capabilities and improved health of the photosynthetic apparatus (Shaari *et al*., 2023; Figueroa *et al*., 2006). A study demonstrated that treating Swiss chard with *Chlorella vulgaris* resulted in increased chlorophyll content, which correlates with enhanced Fm values, indicating improved light absorption and energy conversion efficiency in photosynthesis (Hajnal-Jafari *et al*., 2020). This enhancement is crucial for maximizing photosynthetic performance, as Fm reflects the maximum capacity of Photosystem II (PSII) to capture light energy for photosynthesis (Moustaka and Moustakas, 2023).

Chlorophyll fluorescence (Fv/Fm) provides information about the state of photosystem II in the thylakoid membranes of chloroplast (Moneruzzaman *et al*., 2011). The Fv/ Fm ratio is particularly significant as it serves as an indicator of the maximum quantum efficiency of PSII. A higher Fv/Fm ratio suggests better photosynthetic performance and plant vitality. The plants treated with algal extracts exhibited significant recovery in Fv/Fm after exposure to stress conditions, suggesting that these extracts enhance the ability of plants to maintain efficient photosynthesis even under adverse environmental factors (Goltsev *et al*., 2016; Solovchenko *et al*., 2022). The chlorophyll content and Fv/Fm ratio as well as gas exchange parameters of *Brassica chinensis* were notably enhanced when treated with micro and macroalgal extracts (Shaari *et al*., 2023). In addition, a researcher found that seed priming with *S. platensis* increased quantum yield (Fv/Fm) in maize plants (Ronga *et al*., 2019). Our study reported that algal extracts treatment significantly increased the stomatal conductance of wax apple leaves. Maybe the algal extracts contain the plant growth regulators or bioactive compounds which stimulate the stomatal opening. Khandaker *et al*. (2018) reported that the exogenous application of plant growth regulators improve the stomatal conductance of okra leaves.

Nutrient uptake

The present study demonstrated that algal extract treatments significantly influenced both macro- and micronutrient contents in the leaves of wax apple (*Syzygium samarangense*) seedlings. Treatment T3 (10.0% of *S. platensis* extract) was identified to enhance the accumulation of essential nutrients, including N, P, K, Mg, Cu, Fe and Mn. In the meantime, T6 (10.0% of *S. polycystum* extract) significantly increased Ca, Mg and Zn in wax apple's leaf as shown in Table 3. The findings correspond with earlier research indicating that algal extracts, especially from Sargassum and Spirulina, serve as efficient biofertilizers, enhancing nutrient absorption in plants (Ammar *et al*., 2022). According to Ghosh *et al*. (2020), algal extracts can improve the bioavailability of micronutrients in plants. Algal extracts of 18 microalgae had efficiently enhanced the uptake of N, P and K of *Solanum lycopersicum* L. (Mutale-Joan *et al*., 2020). *Ascophyllum nodosum* was observed to increase the uptake of macronutrients in soybean plant (Engel *et al*., 2023). The similar algal extract was reported to enhance N, P, K, Ca, Mg, Fe, Zn, Mn, and Cu levels in grapes (Turan and Köse, 2004).

Effective nutrient absorption in plants is crucial as it affects photosynthetic efficiency and biomass accumulation (Fathi, 2022). The release of nutrients from organic or inorganic sources may be responsible for the growth and development of plant (Khandaker *et al*., 2017). The capacity of T3 to significantly enhance the micronutrient content suggests that the formulation of this treatment effectively improves nutrient uptake, potentially due to the presence of bioactive compounds that facilitate nutrient mobilization within plant tissues (Lakshani *et al*., 2024). Algal extracts include an extensive variety of bioactive chemicals, including amino acids, peptides, carbohydrates, and growth regulators (e.g., auxins, cytokinins, and gibberellins), which are recognized for their effects on plant growth and the uptake of nutrients (Shaari *et al*., 2023). These bioactive chemicals can improve root development, thus increase the root surface area, allowing plants to access more nutrients from the soil (Mutale-Joan *et al*., 2020). According to Kaur and Purewal (2019), when applied in optimal concentrations, these compounds can interact with plant physiological processes to increase nutrient availability, uptake, and translocation.

Conclusions and Recommendations

This study highlights the significant potential of *S. platensis* and *S. polycystum* extracts as eco-friendly biostimulants in enhancing the physiological performance and nutrient dynamics of wax apple seedlings. Treatments T3 (10.0% *S. platensis* extract) and T6 (10.0% *S. polycystum* extract) were particularly effective, demonstrating notable improvements in photosynthetic pigments, chlorophyll fluorescence, stomatal conductance, and macro- and micronutrient uptake in wax apple seedlings. The findings emphasize the role of algal bioactive compounds in optimizing nutrient absorption and promoting plant growth through improved photosynthetic efficiency and physiological functions. The positive correlation between algal extract concentration and nutrient uptake observed in this study suggests that tailored formulations of algal extracts can be used to optimize nutrient management in horticultural practices, offering a sustainable approach to enhancing plant growth and nutritional quality.

Acknowledgments

The authors sincerely thank Universiti Sultan Zainal Abidin (UniSZA) for its support in this research. The provision of laboratory facilities and research instruments was instrumental in the successful completion of this study. The authors deeply appreciate the provision of the resources and assistance.

Novelty Statement

The study provides novel information on algal extract's effects on the physiology and nutrient uptake of wax apple seedlings

Authors Contribution

Md. Tajol Faeiz Md. Tajudin: Experiment conduction, data curation and analysis, manuscript writing.
Mohammed Moneruzzaman Khandaker: Supervising, project planning and manuscript editing.
Nurul Elyni Mat Shaari: Data analysis, manuscript writing and editing.
Nor Hasima Mahmod: Supervising

Conflict of interest
The authors have declared no conflict of interest.

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