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Optimizing bitter gourd (*Momordica charantia*) production through carrageenan-fertilizer synergy

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Abstract. *Anayatin AB, Pabiona MG, Cristobal JU, Tan R, Labajo JRN. 2025. Optimizing bitter gourd (Momordica charantia) production through carrageenan-fertilizer synergy. Nusantara Bioscience 17: 169-177.* This study evaluates the synergistic effects of combining radiation-modified Carrageenan Plant Growth Promoter (PGP) with the Recommended Rate of Inorganic Fertilizer (RRIF) on the growth, nutrient dynamics, and yield of *Momordica charantia* L. (bitter gourd or *ampalaya*). Through a Randomized Complete Block Design (RCBD) replicated three times, treatments integrating RRIF and Carrageenan PGP were tested for their impact on plant height, soil properties, nutrient content, and fruit morphology. Results revealed that *Full RRIF + 4.5L ha^{-1} Carrageenan PGP* significantly enhanced fruit yield (64.50 tons ha^{-1}) and achieved the highest return on investment (ROI: 435.30%), underscoring its economic viability. Meanwhile, ½ RRIF + 9L ha^{-1} Carrageenan PGP produced the largest fruit diameter (49.44 mm) and highest total nitrogen (2.60%) and crude protein (16.24%) content, highlighting its role in improving nutritional quality. Mid-growth plant height (29 DAT) exhibited strong correlations with fruit weight (r = 0.475), length (r = 0.482), and diameter (r = 0.647), emphasizing the critical role of vegetative vigor in later stages for optimizing fruit development. Notably, earlier flowering (26 DAT under Full RRIF) correlated negatively with fruit weight (r = -0.558) and length (r = -0.532), suggesting accelerated reproductive phases enhance resource allocation to fruit traits. Carrageenan PGP applications stabilized soil moisture (92.30-93.82%) and maintained adequate phosphorus/potassium levels while significantly boosting soil organic matter (1.48%) and nitrogen content (0.074%) in Full RRIF treatments. The stability of these soil parameters, coupled with enhanced nutrient partitioning efficiency, positions Carrageenan PGP as a sustainable alternative to conventional fertilization. This study advocates for integrating Carrageenan PGP with reduced inorganic fertilizers to balance productivity, soil health, and economic returns. Future research should explore long-term impacts on soil microbial diversity, carbon sequestration, and scalability across diverse agroecological zones to refine protocols for sustainable *M. charantia* cultivation.

Keywords: Carrageenan, kappa-Carrageenan, *Momordica charantia*, nutrient content, plant growth promoter, soil properties

Abbreviations: OM: Organic Matter, PGP: Plant Growth Promoter, RMKC: Radiation-Modified Kappa-Carrageenan, ROI: Return on Investment, RRIF: Recommended Rate of Inorganic Fertilizer

INTRODUCTION

Through the years, farmers have optimized yield using inorganic fertilizers alone. Typically, the essential nutrients from fertilizer inputs form part of the optimum production of crops. Still, it also contributes to a significant portion of total crop input costs, leading to many farmers having difficulty. Still, they also contribute to a significant portion of total crop input costs, leading to many farmers having difficulty financing their agricultural inputs. Managing fertilizer inputs is essential as it can constitute a considerable portion of total crop input costs. Research also showed that the dependent use of inorganic fertilizers as a source of nutrients and nourishing agricultural lands resulted in soil degradation. The soil's pH level has changed significantly due to the excessive application of inorganic fertilizers. Most agricultural lands have become unproductive and infertile.

The soil degradation problem calls for mandatory fertilizer application in growing crops. Today, half of the world's population depends on synthetic fertilizers, especially nitrogen (Erisman and Sutton 2008). However, it was mentioned by Dikitanan et al. (2017) that in addition to being very costly, continuous use of synthetic fertilizer could also damage the environment by building up toxic and hazardous chemicals in soil, air, and groundwater, thereby threatening biodiversity. Thus, organic farming is suggested by (Mavuri et al. 2020) to help attain the Sustainable Development Goal (SDG-15) (life on land).

Recent studies have emphasized the advantages of combining organic and inorganic fertilizers. Combining these fertilizers has enhanced soil health by improving microbial biomass, leading to more sustainable soil productivity (Tao et al. 2015; Ozlu et al. 2019). This integrated approach is essential in vegetable production, where high nutrient demands necessitate a balance between maintaining soil fertility and achieving high yields. Experiments conducted across various countries have demonstrated that relying solely on inorganic fertilizers is insufficient for sustaining soil productivity under intensive cropping systems. The need for a continued increase in production and per-hectare yield of vegetables requires increased nutrients (Fernández et al. 2022; Miñoza et al. 2023). The results of several studies on inorganic and organic fertilizers showed that very intensive farming systems could not be sustained by inorganic fertilizers alone (Ilahi et al. 2020; Qaswar et al. 2020). Therefore, combined organic and inorganic fertilizers fix that issue by providing proper nutrients as necessary; essential macro elements like NPK can help the plants grow quickly and strongly (Shaji et al. 2021; Francisco et al. 2022).

An emerging area of interest is plant-derived extracts, such as seaweed-based fertilizers, to reduce dependence on synthetic fertilizers. In the Philippines, the Department of Science and Technology's Philippine Nuclear Research Institute (DOST-PNRI) developed a seaweed emulsion called Carrageenan, derived from red edible seaweed. When this undergoes radiation, natural bioactive agents develop. The process produces oligo-carrageenan polymers with shorter chains, which have been shown to have antibiotic, antioxidant, and Plant Growth-Promoting (PGP) properties and are high in Potassium (K), Magnesium (Mg), and Calcium (Ca), which help to improve the growth, development, and immune system of rice. According to (Gatan et al. 2020), the red seaweed *Kappaphycus alvarezii* (Doty) Doty ex P.C.Silva is a significant source of κ-carrageenan. It contains Nitrogen, Potassium (K2O), Calcium, Manganese, Copper, Zinc, Magnesium (MgO2), Iron, and gibberellic acid. Research conducted by various Philippine agricultural institutions has demonstrated the effectiveness of Radiation-Modified Kappa-Carrageenan (RMKC) in enhancing crop yields. Studies have shown that applying RMKC significantly increases the yield of rice, peanuts, and mung beans (Abad et al. 2018a; Gatan et al. 2020). These findings suggest that Carrageenan Plant Growth Promoter (PGP) can be a valuable addition to the range of inputs used in farming, offering a cost-effective and environmentally friendly alternative to traditional inorganic fertilizers.

This study aims to evaluate the impact of Carrageenan PGP on the growth and yield performance of *M. charantia*. Given the rising costs of inorganic fertilizers, there is a pressing need for alternative solutions that optimize crop yields while being economically viable and environmentally sustainable. Specifically, this research seeks to (i) assess the growth and yield of *M. charantia* Mestiza F1 under varying combinations of inorganic fertilizer and Carrageenan PGP; (ii) determine which combination rate offers the highest return on investment; (iii) evaluate the post-harvest chemical properties of the soil; and (iv) analyze the nutrient content of *M. charantia* fruits in response to different treatment combinations. This study will provide essential scientific data to support *M. charantia* farming with innovative and sustainable agricultural practices.

MATERIALS AND METHODS

Study area

The study was conducted at Purok Mabuhay, Barangay San Isidro, Koronadal City, South Cotabato, Philippines, from April 14 to August 9, 2021, as shown in Figure 1. The area is approximately 6°26'34.4"N 124°51'21.6" E on the Island of Mindanao, with an elevation of about 227.4 meters above sea level (masl). Koronadal City has a tropical climate and significant yearly rainfall, even during the driest months.

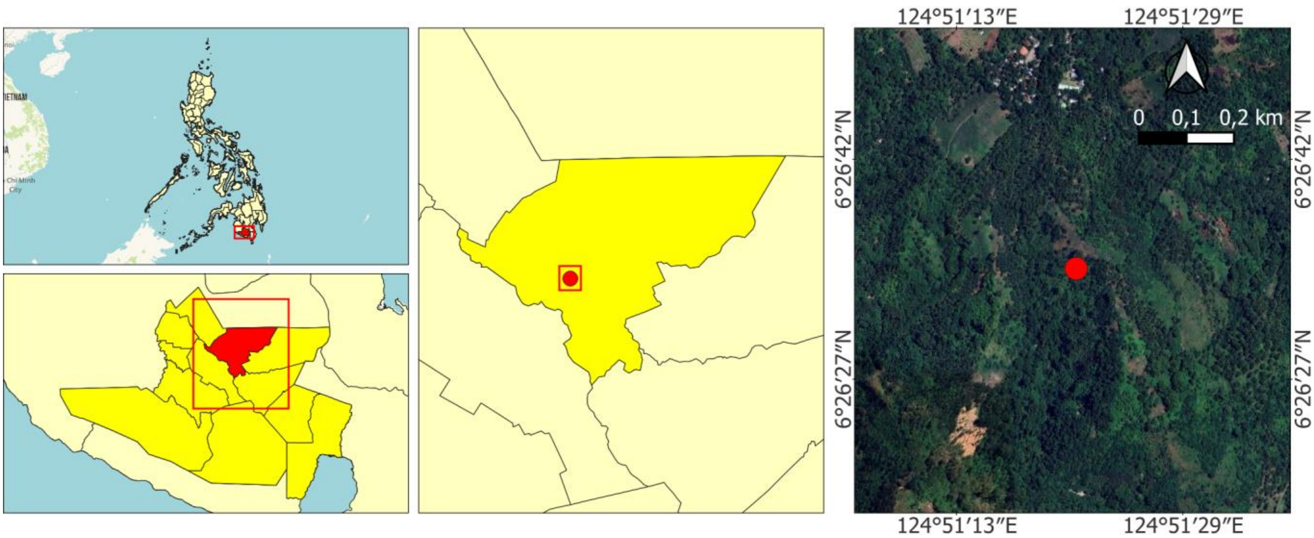

Figure 1. Location of the study site at Koronadal City, South Cotabato, Philippines

Experimental design and treatments

The study was conducted in an area of 870 m^2. Soil samples were taken from the experimental area for initial soil characterization one 1 month before transplanting. Composite soil samples were analyzed at the Soil and Plant Analysis Laboratory (SPAL) at the Department of Soil Science, College of Agriculture, Central Mindanao University, Musuan, Maramag, Bukidnon, to obtain the Recommendation Rate of Inorganic Fertilizer (RRIF). The study was laid out in a Randomized Complete Block Design (RCBD), with seven (7) treatments replicated three (3) times. Mestiza F1 hybrid *ampalaya*/bitter gourd seeds (*Momordica charantia* L.) were used. The experimental area was divided into three (3) blocks, which measured three (3) meters in width by six (6) meters long, with a buffer zone of two (2) meters distance observed between treatments and each block. Varying amounts of Carrageenan PGP per hectare served as a variable. VitalGro® Carrageenan PGP is a radiation-modified plant growth promoter developed by the Philippine Nuclear Research Institute (PNRI) under the Department of Science and Technology (DOST). It is derived from *K. alvarezii*, a red edible seaweed ("guso" or "gulamang dagat") native to the Philippines (Mariano Marcos State University 2018; Philippine Nuclear Research Institute 2022). The treatments were as follows: T_1- Absolute Control; T_2- Full RRIF (60-30-50); T_3- ½ RRIF; T_4- 9 L ha^{-1} Carrageenan PGP; T_5- ½ RRIF + 9L ha^{-1} Carrageenan PGP; T_6- ½ RRIF + 4.5L ha^{-1} Carrageenan PGP; and, T_7- Full RRIF + 4.5L ha^{-1} Carrageenan PGP.

Cultural and management practices

The cultivation practices detailed for *M. charantia* (bitter melon) encompass a comprehensive approach to optimize growth and yield. The preparation of the planting area involved thorough plowing and harrowing, creating well-prepared beds covered with plastic mulch to maintain soil moisture and suppress weeds. Seedling preparation was meticulous, with sowing in trays containing sterilized media and precautionary fungicide treatment to prevent damping off. Transplanting followed rigorous protocols, including vermicompost application for nutrient enrichment, precise spacing, and immediate watering for establishment. Fertilization strategies were tailored to soil analysis, employing deep placement techniques to minimize nutrient loss, supplemented by Carrageenan Plant Growth Promoter (PGP) application was done as foliar in the 3^{rd}, 5^{th}, 7^{th}, 9^{th}, and 11^{th} week after transplanting; it was applied separately in the application of inorganic fertilizer, for enhanced growth and stress tolerance. Trellising and pruning techniques were used to promote vine growth and fruit development (Khan et al. 2022). Integrated pest management techniques were also used to control pests and diseases. Regular water management, weeding, and harvesting protocols ensured optimal plant health and fruit quality throughout the cultivation cycle, demonstrating a holistic approach to sustainable *M. charantia* production.

Collection and preparation of soil and fruit samples for analysis

After harvest, a soil sample was collected between hills in each experimental plot. Soil sampling was done from the surface to 10-15 cm depth. The collected soil sample was placed in a plastic bag and air-dried at room temperature for at least one week. The soil sample was sieved using a 2 mm mesh sieve and brought to the Soil and Plant Analysis Laboratory (SPAL) for soil analysis. Fruit samples were taken from each experimental plot in the eighth harvest; they were cleaned and dried immediately using dry clothes or tissue paper. Drying was done using a forced draft oven with a temperature of 65-70°C. The sample was pulverized and dried again overnight at 70°C before analysis.

The following soil properties were determined from the soil samples: soil pH using the Potentiometric Method (1:5 soil-water ratio) as described by Biddle (1997); OM content using the Walkley-Black Method (PCARRD 1991); extractable phosphorus (P) using the Bray P2 method (PCARRD 1991); exchangeable potassium (K) using 1 N NH4OAc at pH 7; and initial soil texture analysis. For the plant samples, the analyses included total Nitrogen (N) using the Micro Kjeldahl method, total phosphorus (P) using the Dry Ashing Vanadomolybdate method with a UV-VIS Spectrometer, and total potassium (K) using Dry Ashing and Atomic Absorption Spectroscopy (AAS) (PCARRD 1991).

Cost and return analysis

The economics of the production process was determined by computing the Return on Investment (ROI). The net income was derived from the difference between the gross income and the total cost of production used in the study. The ROI was computed using the formula. ROI Net income divided by the cost of production × 100. Where: Net income = Gross income – Total cost of production.

Statistical analysis

Data was analyzed using ANOVA in a Randomized Complete Block Design (RCBD). The HSD Test was used to compare treatment means that differed significantly. All statistical analyses were performed using the IRRI STAR Nebula software.

RESULTS AND DISCUSSION

Horticultural and characteristics of *Momordica charantia* as affected by the treatment

Plant height of Momordica charantia

The plant height of *M. charantia* at 15 and 29 days after transplanting, as influenced by the different treatment combinations, is presented in Table 1. The result showed no variation among the treatments on the plant height at 15 days after transplanting, with mean values ranging from 45.03 to 51.75 cm. However, the T_1 absolute control obtained a highly significant difference among the treatments, while in T_2, T_3, T_4, T_5, T_6, and T_7, no significant differences were observed among the treatment means on the height of the plants at 29 days after transplanting. In contrast, the plants applied with ½ RRIF + 9L ha^{-1} Carrageenan PGP (T_5), ½ RRIF + 4.5L ha^{-1} Carrageenan PGP (T_6), Full RRIF + 4.5L ha^{-1} Carrageenan PGP (T_7), 9 L ha^{-1} Carrageenan PGP (T_4), Full RRIF (T_2), and ½ RRIF (T_3) produced the tallest plants having mean values ranging from 227.19 to 231.14 cm, respectively. The shortest plants were found on the control plants (T_1) with a mean value of 183.69 cm.

Despite insignificant variances among treatments, the application of Carrageenan PGP caused greater height than that without Carrageenan PGP. The result indicates that Carrageenan PGP is promising because its effect is similar to that of inorganic fertilizer regarding *M. charantia* plant height. The results are consistent with the research of Khan et al. (2009), which states that seaweed formulations are widely used as biostimulants in crop production and that seaweed products have growth-stimulating properties. These materials promote plant growth when applied in small quantities. The cellular metabolism of treated plants is influenced by seaweed components, including macro- and microelements, amino acids, vitamins, cytokinins, auxins, and compounds that resemble abscisic acid (ABA). This increases plant growth and yield (Kocira et al. 2019; Chaturvedi et al. 2022).

Days of the first flowers appearance

The days of the first flower appearance after transplanting, as influenced by the different treatment combinations, are presented in Table 1. There is no significant difference among treatments. The first flower appearance was observed 26 days after transplanting (T2) with the application of the full Recommended Rate of Inorganic Fertilizer (RRIF). Among the seven treatments, the last flower appearance was observed in Treatment 1 (absolute control), 31.67 days after transplanting. The same flower appearance was observed 27.33 days after transplanting in the treatment T4, the application of 9 L ha^{-1} Carrageenan PGP, and T6, the application of ½ RRIF + 4.5L ha^{-1} Carrageenan PGP.

Average weight, length, diameter, and fruit yield of *Momordica charantia*

Table 2 presents *M. charantia* fruits' average weight, length, and diameter, as influenced by the different treatment combinations. The results showed no significant difference between treatments regarding *M. charantia* fruits' average weight and length. The average weight of *M. charantia* fruits ranges from 210.33 grams to 240.48 grams. In contrast, the average size of *M. charantia* fruits ranges from 255.43 to 277.50 mm.

The combination of treatments influenced the fruit diameter. The plants applied with ½ RRIF + 9L ha^{-1} Carrageenan PGP (T_5) and full RRIF (T2) applied the biggest, most significant mean values of 49.44 and 48.91 mm. It was followed by ½ RRIF + 4.5L ha^{-1} Carrageenan PGP (T6), Full RRIF + 4.5L ha^{-1} Carrageenan PGP (T_7), ½ RRIF (T_3), and 9 L ha^{-1} Carrageenan PGP (T_4) with mean values of 48.63, 48.46, 47.24, and 46.36 mm. The smallest diameter was observed at absolute control (T_1) with 44.68 mm. As a result of its composition of macro and microelements, vitamins, cytokinins, auxins, and abscisic acid (ABA)-like growth substances, Carrageenan PGP was found to have a significant impact on the fruit development of *M. charantia*. This enhanced growth and crop yield in treated plants (Butay 2017; Mondal et al. 2020; Chaturvedi et al. 2022).

It was generally observed that Treatment 5, the application of ½ Recommended Rate of Inorganic Fertilizer (RRIF) plus 9 liters of Carrageenan PGP per hectare, obtained the highest average length of 277.50 mm and diameter of 49.44 mm. In contrast, T_2- Full application of the Recommended Rate of Inorganic Fertilizer (RRIF) alone recorded the highest average weight of 246.90 g. In comparison, absolute control (T_1) acquired the lowest average weight, length, and diameter of 210.33 g, 255.43 mm, and 44.68 mm, respectively.

Table 1. Plant height (cm) of *Momordica charantia* plant 15 and 29 DAT, and days of first flower appearance as affected by the different treatment combination

Treatment	Plant height 15 (DAT)	Plant height 29 (DAT)	Days of first flowers appearance (DAT)
T_1- Absolute Control	47.83±1.83	183.69±3.94 b	31.67±2.52
T_2- Full RRIF	45.03±2.35	228.33±19.74 a	26.00±2.65
T_3- ½ RRIF	48.86±5.39	227.19±14.11 a	29.00±3.61
T_4- 9 L ha^{-1} Carrageenan PGP	47.03±2.71	229.97±5.34 a	27.33±1.53
T_5- ½ RRIF + 9L ha^{-1} Carrageenan PGP	48.61±3.17	231.14±10.40 a	28.67±3.79
T_6- ½ RRIF + 4.5L ha^{-1} Carrageenan PGP	49.11±2.36	230.78±9.76 a	27.33±5.13
T_7- Full RRIF + 4.5L ha^{-1} Carrageenan PGP	51.75±5.81	230.56±32.97 a	28.00±5.57
Mean	48.32±2.06	223.09±17.43	28.29±1.79
F-test	ns	*	ns
CV, %	7.14	4.87	12.46

Note: Data are presented as mean ± standard deviation (n = 3 replications). Means within a column followed by the same letter are not significantly different at *p* < 0.05 (Tukey's HSD). RRIF: Recommended Rate of Inorganic Fertilizer; PGP: Plant Growth Promoter; ns: not significant; *: significant; CV: Coefficient of Variation

Table 2. Average weight, length, diameter, fruit yield, and % ROI of *Momordica charantia* fruits as affected by the different treatment combinations

Treatment	Average fruit weight (g)	Average fruit length (mm)	Average fruit diameter (mm)	Fruit Yield (tons ha^{-1})	% ROI
T_1- Absolute Control	210.33±2.89	255.43±1.74	44.68±0.51 b	28.49±5.21 d	154.25±46.50d
T_2- Full RRIF	246.90±15.03	276.20±6.41	48.91±1.55 a	53.48±10.98 ab	371.19±128.42ab
T_3- ½ RRIF	228.47±7.16	269.15±4.32	47.24±1.38 ab	41.62±2.88 bc	252.14±25.64bcd
T_4- 9 L ha^{-1} Carrageenan PGP	224.01±32.05	263.51±20.61	46.36±1.99 ab	34.01±6.34 cd	191.91±53.89cd
T_5- ½ RRIF + 9L ha^{-1} Carrageenan PGP	240.10±7.05	277.50±2.00	49.44±1.69 a	44.87±7.79 bc	279.11±64.85bcd
T_6- ½ RRIF + 4.5L ha^{-1} Carrageenan PGP	239.42±7.84	276.98±5.24	48.63±1.02 ab	49.62±7.65 b	317.29±65.73abc
T_7- Full RRIF + 4.5L ha^{-1} Carrageenan PGP	240.48±7.09	275.82±7.89	48.46±2.16 ab	64.50±6.17 a	435.30±51.62a
Mean	232.81±12.62	270.66±8.46	47.67±1.69	45.23±12.10	287.53±98.77
F-test	ns	ns	*	**	**
CV, %	5.59	3.21	3.06	9.71	17.17

Note: Data are presented as mean ± standard deviation (n = 3 replications). Means within a column followed by the same letter are not significantly different at *p* < 0.05 (Tukey's HSD). RRIF: Recommended Rate of Inorganic Fertilizer; PGP: Plant Growth Promoter; ns: not significant; *: significant; **: highly significant; CV: Coefficient of Variation

Table 3. Soil pH, OM, and total nitrogen content of the soil after harvest as affected by the different treatment combinations

Treatment	pH	Organic matter %	Total Nitrogen %	Extractable P (mg kg^{-1})	Exchangeable K (cmol kg^{-1})
T_1- Absolute Control	6.61±0.11	0.59±0.02 c	0.030±0.00 c	98.05±4.30	0.71±0.13
T_2- Full RRIF	6.57±0.10	1.48±0.14 a	0.074±0.01 a	108.87±9.34	0.64±0.14
T_3- ½ RRIF	6.54±0.10	0.96±0.08 b	0.048±0.00 b	107.50±8.87	0.77±0.01
T_4- 9 L ha^{-1} Carrageenan PGP	6.82±0.08	0.90±0.02 b	0.045±0.01 b	111.27±7.45	0.67±0.03
T_5- ½ RRIF + 9L ha^{-1} Carrageenan PGP	6.71±0.25	0.69±0.03 c	0.034±0.01c	113.30±4.74	0.79±0.08
T_6- ½ RRIF + 4.5L ha^{-1} Carrageenan PGP	6.81±0.05	0.58±0.01 c	0.029±0.00 c	110.20±6.08	0.85±0.17
T_7- Full RRIF + 4.5L ha^{-1} Carrageenan PGP	6.85±0.03	0.98±0.05 b	0.049±0.00 b	109.32±7.50	0.82±0.10
Mean	6.07±0.13	0.88±0.31	0.044±0.01	108.36±4.91	0.75±0.08
F-test	ns	*	*	ns	ns
CV, %	1.66	7.67	7.66	5.67	14.20

Note: Data are presented as mean ± standard deviation (n = 3 replications). Means within a column followed by the same letter are not significantly different at *p* < 0.05 (Tukey's HSD). RRIF: Recommended Rate of Inorganic Fertilizer; PGP: Plant Growth Promoter; ns: not significant; *: significant; CV: Coefficient of Variation

Return on investment

The return on investment of *M. charantia*, as influenced by the different treatment combinations, is presented in Table 2. The result showed that there is a highly significant difference among treatments. Treatment 7, applying full RRIF plus 4.5 liters per hectare of Carrageenan PGP, obtained a fruit yield of 64.50 tons ha^{-1} with a corresponding return on investment of 435.30%. The lowest return on investment of 154.25% was recorded in treatment 1 (absolute control), with a corresponding yield of 28.49 tons ha^{-1}. Treatment 7 obtained a highly significant difference among the treatments. According to Abad (2018b), carrageenan PGP increased rice yields by as much as 30% compared to average farmer practices. In general findings, carrageenan PGP is also effective in *M. charantia* production as a supplement.

Chemical properties of the soil after harvest

Soil properties, including pH, OM percentage, total nitrogen percentage, extractable phosphorus (P), and exchangeable potassium (K) affected by different treatments, are shown in Table 3. The treatments involve varying Reduced-Rate Inorganic Fertilizer (RRIF) and Carrageenan Plant Growth Promoter (PGP) combinations. The results show significant differences in OM and total nitrogen content among the treatments. At the same time, pH, extractable phosphorus, and exchangeable potassium remain unaffected. Specifically, the application of Full RRIF (T2) significantly increased OM (1.48%) and total Nitrogen (0.074%) compared to the control and other treatments. Treatments involving half RRIF with or without PGP showed moderate improvements in these soil properties. However, extractable phosphorus and exchangeable potassium did not show significant differences across treatments, suggesting that these elements are stable irrespective of the applied treatments.

The variations in soil OM and total Nitrogen, as shown in Table 3, are crucial for the growth and development of *M. charantia* (bitter melon). This research underscores the importance of soil OM and nitrogen content, mainly observed in the Full RRIF treatment (T2), which can enhance soil fertility and improve nutrient availability, essential for *M. charantia* plants' strong growth. Higher OM enhances soil structure, water retention, and microbial activity, creating a more conducive environment for root development and nutrient uptake. The significant increase in total Nitrogen, a critical component of chlorophyll and amino acids, can promote vigorous vegetative growth, leading to healthier plants and potentially higher yields.

Table 4. Moisture content and dry matter (%) of *Momordica charantia* fruits as affected by the different treatment combinations

Treatment	Moisture content (%)	Dry matter (%)
T_1- Absolute Control	93.63±0.81	6.37±0.81
T_2- Full RRIF	93.31±0.75	6.69±0.75
T_3- ½ RRIF	92.30±0.95	7.70±0.95
T_4- 9 L ha^{-1} Carrageenan PGP	93.82±0.54	6.18±0.54
T_5- ½ RRIF + 9L ha^{-1} Carrageenan PGP	93.74±0.44	6.26±0.44
T_6- ½ RRIF + 4.5L ha^{-1} Carrageenan PGP	93.52±0.26	6.48±0.26
T_7- Full RRIF + 4.5L ha^{-1} Carrageenan PGP	93.58±0.76	6.42±0.76
Mean	93.41±0.52	6.59±0.52
F-test	ns	ns
CV, %	0.7075	10.03

Data are presented as mean ± standard deviation (n = 3 replications). Means within a column followed by the same letter are not significantly different at *p* < 0.05 (Tukey's HSD). RRIF: Recommended Rate of Inorganic Fertilizer; PGP: Plant Growth Promoter; ns: not significant; CV: Coefficient of Variation

While the pH, extractable phosphorus, and exchangeable potassium levels show no significant differences among treatments, the consistent levels across treatments indicate that these soil properties are inherently stable in the given conditions. A farmer's understanding of soil pH is crucial since many plants and soil organisms prefer either alkaline or acidic conditions (Tale and Ingole 2015). The lack of significant change in phosphorus and potassium suggests that the existing soil conditions already provide adequate nutrients for *M. charantia* growth. This stability can be beneficial as it prevents potential nutrient imbalances affecting plant health. However, the enhanced OM and nitrogen content from the Full RRIF treatment provides a more nutrient-rich soil environment, which could lead to improved growth and productivity of *M. charantia*. Therefore, for optimal growth and yield. Focusing on treatments that boost OM and Nitrogen without disrupting other soil properties could benefit *M. charantia* cultivation.

Moisture content and dry matter of *Momordica charantia* fruit as affected by the treatments

The table presents an analysis of moisture content (%) and dry matter (%) in *M. charantia* subjected to various agricultural treatments in Table 4. These treatments include combinations of Reduced-Rate Inorganic Fertilizers (RRIF) and Carrageenan Plant Growth promoters (PGP). The results indicate minimal variation in moisture content across treatments, with values ranging from 92.30 to 93.82%. The F-test showed no significant differences among treatments, suggesting that RRIF and Carrageenan PGP applications did not markedly affect the moisture levels of the fruit. Conversely, significant differences were observed in dry matter content, ranging from 6.18 to 7.70%. Treatments with half the recommended RRIF dose (T3) exhibited the highest dry matter content, indicating increased nutrient concentration and potential improvements in fruit quality. These results emphasize the significance of nutrient management strategies in influencing the physiological aspects of *M. charantia*, such as nutrient uptake and assimilation, which directly impact on its market value and consumer acceptance.

Moisture content is crucial in determining *M. charantia* post-harvest quality and storage stability. The consistent moisture levels observed across treatments suggest that the variations in RRIF and Carrageenan PGP applications did not disrupt water uptake or translocation within the fruit. This stability is beneficial as it ensures uniformity in texture and juiciness, contributing to consumer satisfaction and marketability. In contrast, the significant differences in dry matter content highlight the influence of fertilization practices on the nutritional composition of *M. charantia*. Higher dry matter content, particularly in treatments with reduced RRIF applications, indicates enhanced nutrient utilization efficiency and potentially improved yield and economic returns for farmers.

Plant tissue chemical properties

Table 5 presents the effects of various treatments on nutrient content and crude protein levels in *M. charantia* (bitter melon). The treatments included Reduced-Rate Inorganic Fertilizer (RRIF) and Carrageenan Plant Growth Promoter (PGP) combinations. Significant differences were observed in total nitrogen (N) and crude protein content among the treatments. Full RRIF (T2) showed the highest values for both parameters. Total Nitrogen ranged from 1.53% in control (T1) to 2.60% in T2, while crude protein content ranged from 9.58% in T1 to 16.24% in T2. Conversely, no significant differences were noted in total phosphorus (P) and total potassium (K) content among the treatments, indicating stable levels of these nutrients across different treatment applications.

The significant increase in total Nitrogen and crude protein content in the Full RRIF treatment (T2) has important implications for the growth and productivity of *M. charantia*. Higher nitrogen levels enhance vegetative growth, leaf chlorophyll content, and overall plant vigor, leading to more robust and productive plants. The increased crude protein content also suggests improved nutritional quality of *M. charantia*, which can benefit both human consumption and market value. These improvements are crucial as they directly impact yield and quality, making Full RRIF a valuable treatment for maximizing the agricultural potential of *M. charantia*. Nitrogen application is more critical than other essential nutrients for successful crop production (Javed et al. 2022). Slow development of plant and early leaf senescence due to deficient N can cause decreased both crop production and quality (Dong et al. 2012), but excess N prolongs the vegetative growth period, delays maturity, decreases sugar content, and attracts insect pests and causes disease epidemics (Anas et al. 2020). Phosphorus is classified as a significant nutrient. Despite crops needing it in relatively high amounts, it is frequently insufficient for crop output. It is an excellent source of magnesium, folic acid, zinc, phosphorus, manganese, and vitamins B1, B2, and B3. It has high dietary fiber (Asna et al. 2020). It was reported that bitter melon is an excellent source of phenolic chemicals, which have strong antioxidant properties (Aminah and Anna 2011). Fruits are relatively high in proteins, minerals, vitamins, and many other nutrients required in the human diet (Krishnendu and Nandini 2016).

Despite the variations in nitrogen and protein content, the stability of phosphorus and potassium levels across treatments ensures that these essential nutrients remain available to support various physiological processes in the plant. Phosphorus is vital for energy transfer and photosynthesis, while potassium is crucial in enzyme activation and osmoregulation. The consistent levels of these nutrients indicate that the different treatment combinations do not disrupt their availability, allowing for balanced growth and development of *M. charantia*. Therefore, while increasing nitrogen availability is important for raising yield and quality, keeping potassium and phosphorus levels steady is just as important for the crop's general health and productivity.

The correlation matrix revealed significant relationships between key growth, phenological, and yield parameters of *M. charantia* shown in Table 6. Plant height at 29 DAT exhibited moderate to strong positive correlations with fruit weight 0.475, length 0.482, and diameter 0.647, suggesting that vegetative growth during later stages strongly influences fruit development. Studies on bitter gourd cultivars under Karaj conditions demonstrated that taller plants (e.g., Hybrid No. 486 at 355.33 cm) produced higher yields and larger fruits, aligning with the role of mid-growth vigor in resource allocation for fruit development (Valyaie et al. 2021). Notably, days to first flowering showed a highly significant negative correlation with fruit weight -0.558 and length -0.532, indicating that earlier flowering promotes larger and heavier fruits. Among yield components, fruit weight, length, and diameter were strongly intercorrelated (0.857-0.901), highlighting their synergistic contribution to overall fruit morphology. Fruit yield demonstrated highly significant correlations with weight 0.674, length 0.676, and diameter 0.554, underscoring the cumulative impact of these traits on productivity.

The weak correlation between early vegetative growth (15 DAT) and yield parameters (0.165-0.304) implies that early-stage plant height is less predictive of final yield compared to mid-growth (29 DAT) and phenological traits. The negative association between days to flowering and yield-related traits suggests that treatments accelerating flowering could enhance fruit development. However, the non-significant correlation between early growth (15 DAT) and yield (0.184) may reflect variability in treatment responses during initial growth phases.

Table 5. Total N, P, K, and crude protein content of *Momordica charantia* fruits as affected by the different treatment combinations, (%)

Treatment	Total N	Total P	Total K	Crude protein
T_1- Absolute Control	1.53±0.14d	0.35±0.04	2.58±0.09	9.58±0.90d
T_2- Full RRIF	2.60±0.29a	0.32±0.04	2.77±0.41	16.24±1.81a
T_3- ½ RRIF	2.27±0.01abc	0.36±0.05	2.94±0.47	14.21±0.04abc
T_4- 9 L ha^{-1} Carrageenan PGP	2.17±0.14abc	0.30±0.03	2.07±0.35	13.57±0.88abc
T_5- ½ RRIF + 9L ha^{-1} Carrageenan PGP	1.83±0.04cd	0.32±0.05	2.95±0.33	11.46±0.25cd
T_6- ½ RRIF + 4.5L ha^{-1} Carrageenan PGP	2.13±0.16bc	0.27±0.12	2.06±0.74	13.34±0.96bc
T_7- Full RRIF + 4.5L ha^{-1} Carrageenan PGP	2.49±0.16ab	0.24±0.03	2.38±0.87	15.57±1.00ab
Mean	2.15±0.37	0.31±0.04	2.54±0.38	13.42±2.30
F-test	**	ns	ns	**
CV, %	7.34	18.03	19.20	7.34

Data are presented as mean ± standard deviation (n = 3 replications). Means within a column followed by the same letter are not significantly different at *p* < 0.05 (Tukey's HSD). RRIF: Recommended Rate of Inorganic Fertilizer; PGP: Plant Growth Promoter; ns: not significant; *: significant; **= highly significant; CV: Coefficient of Variation

Table 6. Correlation analysis of growth, phenological, and yield parameters in *Momordica charantia* as affected by the different treatment combinations

Variable	Plant height 15 (DAT)	Plant height 29 (DAT)	Days of first flowers appearance	Average fruit weight	Average fruit length	Average fruit diameter	Fruit yield
Plant height 15 (DAT)	1.000						
Plant height 29 (DAT)	0.402	1.000					
Days of first flowers appearance (DAT)	-0.365	-0.384	1.000				
Average fruit weight	0.165*	0.475*	-0.558**	1.000			
Average fruit length	0.304	0.482*	-0.532*	0.901**	1.000		
Average fruit diameter	0.234	0.695	-0.526*	0.857**	0.798**	1.000	
Fruit yield	0.184	0.289	-0.412	0.674**	0.676**	0.554**	1.000

Correlation coefficients (Pearson's *r*) are shown; *: significant at *p* < 0.05, **: highly significant at *p* < 0.01. DAT: Days After Transplanting. Data derived from 3 replications per treatment

In conclusion, the study results indicate that the application of Recommended Rate Inorganic Fertilizer (RRIF) and Carrageenan Plant Growth Promoter (PGP) significantly influences various aspects of *M. charantia* cultivation. The findings highlight that specific combinations of RRIF and PGP can effectively enhance plant growth parameters, promote early flowering, improve soil pH and OM content, increase nutrient availability, and enhance protein levels in *M. charantia*. These results highlight the importance of tailored fertilization strategies and PGP applications in optimizing crop yield, quality, and nutritional value. This study demonstrates that integrating Carrageenan-based Plant Growth Promoters (PGP) with inorganic fertilizers significantly enhances the growth, yield, and nutritional quality of *M. charantia* while improving soil health. Key findings reveal that treatments combining reduced inorganic fertilizer (½ RRIF) with Carrageenan PGP (T5: ½ RRIF + 9L ha^{-1} PGP) optimized fruit diameter (49.44 mm) and nutrient content, whereas full RRIF with PGP (T7) achieved the tallest plants (260.42 cm) and highest yield (64.50 tons/ha). Notably, carrageenan PGP mitigated the reliance on synthetic fertilizers, improving soil organic matter (OM) and nitrogen content without destabilizing pH or phosphorus/potassium levels. The strong correlation between mid-growth vigor (29 DAT) and fruit traits (0.475-0.857**) underscores the importance of late-stage vegetative development in yield outcomes. However, early growth (15 DAT) showed minimal predictive value for productivity, emphasizing the need for targeted mid-growth interventions. These results validate carrageenan PGP as a sustainable alternative to conventional practices, balancing economic viability (435% ROI for T7) with environmental stewardship. Moreover, the study reveals that while the moisture content of the fruits remained relatively stable across different treatments, the dry matter content varied significantly, with the highest dry matter observed in treatments with reduced RRIF.

To optimize *M. charantia* production sustainably may explore integrating carrageenan PGP with inorganic fertilizers, such as prioritizing combinations like ½ RRIF + 9L ha^{-1} PGP (T5) for enhanced fruit quality or Full RRIF + 4.5L ha^{-1} PGP (T7) to maximize yield and vegetative growth, depending on market needs. Prioritizing mid-growth monitoring (29 DAT) over early-stage assessments could improve yield predictions, as plant height at this stage strongly correlates with fruit traits. Exploring long-term soil health impacts, including microbial diversity and carbon sequestration under carrageenan PGP use, alongside trials across diverse crops, may validate broader applicability. Conducting cost-benefit analyses tailored to smallholder farmers can refine adoption strategies, balancing economic and environmental benefits. Integrating Carrageenan PGP into existing practices offers a pathway to harmonize productivity, profitability, and ecological resilience in *M. charantia* cultivation. Future research might also examine long-term effects on soil fertility, environmental sustainability, and dietary benefits to enhance agricultural practices for similar crop systems.

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