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Assessment of the Red Seaweed *Gelidium sesquipedale* By-Products as an Organic Fertilizer and Soil Amendment

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Abstract: The agar extraction process of the red algae *Gelidium sesquipedale* generates a solid residue as the main by-product. However, this residue remains non-valorized, despite its potential as a fertilizer. This study aims to determine the value of *G. sesquipedale* residue as organic fertilizer and for soil amendments. An incubation test of *G. sesquipedale* residue in soils was performed to measure the nitrogen (N), phosphorus (P), and calcium (Ca) release. The potential fertilization effect of the residue was evaluated in a greenhouse on two crops: strawberry and corn. The amount of available P was high at the beginning of the incubation experiment. The amounts of nitrate–nitrogen (NO_3^--N) and available Ca increased over the incubation time. A high efficiency of fertilization using the residue at different concentrations was observed in both crops. Application of the residue enhanced crop growth. The fertilization effect was associated with increased macro- and micro-elements in the strawberry fruit's N, Ca, iron (Fe), manganese (Mn), and zinc (Zn) and in the corn leaves' N, P, magnesium (Mg), and Fe. Moreover, the residue was a good soil organic amendment as it enhanced the amount of organic matter (OM) and some macro- and micro-elements in the soil after plant harvest.

Keywords: red algae residue; fertilization; strawberry; corn; organic matter

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1. Introduction

Plants need nutrients for their growth and development, especially macro-elements, nitrogen (N), phosphorus (P), potassium(K), calcium (Ca), magnesium (Mg), and micro-elements such as iron (Fe), zinc (Zn), manganese (Mn), and boron(B) to produce high yields of good quality [1]. Therefore, synthetic fertilizers are used to enhance crop yields [2]. Synthetic fertilizers cause many health problems and environmental pollution [3]. The continuous utilization of chemical fertilizers leads to decreased soil quality by reducing soil organic matter [4]. The decline in soil fertility is occurring in large parts of the world, essentially in arid and semi-arid regions where the organic matter (OM) content is generally low (1.5%) [5]. The loss of soil organic matter affects the amount of water stored in the soil [6]. The production of bread through the cultivation of wheat using synthetic ammonium nitrate fertilizer generated 40% of the environmental impact of greenhouse gas emissions [7]. Moreover, the utilization of chemical fertilizers increases the risk of water eutrophication [8]. The use of sustainable fertilization by applying biofertilizers such as raw manure and composts can replace or reduce the employment of synthetic fertilizers, enhance plant yields, minimize the impact on the environment, and improve soil properties [9,10]. Organic fertilizers reduce nitrate leaching into the environment [11]. The adaptation of biological systems will create a healthy ecosystem and natural environment for present and future generations [12]. Alternative sources of organic fertilizers that provide plants with an optimal combination of macro-elements, secondary elements, and micro-elements and that improve plant yields, chemical characteristics, and soil quality would be extremely beneficial to agricultural production.

Algae have long been used as biofertilizers in agriculture [13]. Many studies have revealed that algae can increase plant growth and yield [14,15]. Indeed, the application of algae improves the speed and percentage of seed germination and enhances the content of macro-elements in plants, particularly that of N, P, and K [16,17]. In addition, the use of algae increases the biochemical parameters of the plants, such as photosynthetic pigments, proteins, amino acids, ascorbic acid, and nitrate reductase, and reduces sugar activity [18]. The application of algae to the soil improves the physical and chemical characteristics without the addition of the secondary elements and micro-elements necessary for a good yield [19]. Similarly, algae have been used to reduce the impact of salt stress on plants through changes in the biochemical and physiological parameters of plants [20]. The *Gelidium* and *Gracilaria* algae are the main raw materials for agar preparation [21]. *Gelidium*-extracted agar has a higher gel strength [22] and lower sulfate content than *Gracilaria* [23]. The cooking step of the *Gelidium sesquipedale* red algae, to extract agar, can generate a large number of unused residues and a high amount of by-products with a good composition of proteins and amino acids composition, similar to that of the original algae [24].

The transformation of organic compounds into plant-available nutrients is completed through decomposition and mineralization by micro-organisms [25]. The rate of available nutrient release from plant residues depends on their biochemical composition [26]. Quantitative information on nutrient mineralization is needed to assess the availability and loss of nutrients in soil [27]. A understanding mineralization and nutrient release from organic compounds after application in soil is essential to guarantee meeting the nutrient demand of crops and to assure timely fertilizer application in order to increase nutrient use efficiency [28]. Mineralization and nutrient release from organic fertilizer can be studied through the laboratory incubation of a soil–fertilizer mixture [29].

No information about the release of nutrients into the soil after the mineralization of *G. sesquipedale* residue and their effects on soil is available.

The objective of this research was to study the fertilizer value of *G. sesquipedale* residues as an organic fertilizer and soil amendment.

2. Materials and Methods

2.1. Residue and Soil Preparation

The residue of *G. sesquipedale*, obtained after agar-agar extraction, was provided by the SETEXAM company (Kenitra, Morocco). The residue was cleaned to remove impurities such as shell fragments and sand and then dried at room temperature for eight days and crushed for use in subsequent analysis and experiments.

The soil used in this study was collected from a potato field in the area surrounding Kenitra city. After air drying, the soil was sieved through a 2 mm mesh. A subsample was taken for analysis and the remainder was used in the incubation and bio-fertilization experiments.

2.2. Residue and Soil Analysis

The residue and soil were analyzed to determine their chemical and physical characteristics. The pH was determined in a residue/soil: water extract (1:2) and measured by an electrode pH meter (Mettler Toledo, Shanghai, China) [30]. The organic matter (OM) was determined by titration with potassium dichromate [31] and organic carbon (OC) was determined by dividing the OM by the factor 1.724. The total N was determined using the Kjeldahl method (Model B-324, Buchi, Switzerland) [32]. NO_3^--N was extracted with distilled water and determined by the chromotropic acid method, and the absorbance was measured with a spectrophotometer at 410 nm (Spectronic, Melville, NY, USA) [33]. Ammonium-N (NH_4^+-N) was extracted with KCL and determined by colorimetry at 636 nm using a Shimadzu spectrophotometer (Shanghai, China). The available P was extracted with sodium bicarbonate and determined colorimetrically at 882 nm [34]. The available Ca was extracted with ammonium acetate and measured by a flame photometer

(Model CL 378, Nanolytik) [35]. The total P, Ca, K, and Mg and micro-elements Fe, Zn, Mn, and copper (Cu) were determined using inductively coupled plasma optical emission spectrometry (ICP-OES). The chemical and physical properties of the used residue and soil materials are summarized in Tables 1 and 2, respectively.

Table 1. Chemical composition of the *G. sesquipedale* residue.

Parameters	Value
pH	7.31
C/N ratio	10.7
Organic C (g/kg)	425
Total N (g/kg)	39.7
NO_3^--N (g/kg)	0.44
NH_4^+–N (g/kg)	0.003
Total P (g/kg)	5.52
Available P (g/kg)	0.67
Total K (g/kg)	1.90
Available K (g/kg)	0.3
Total Mg (g/kg)	3.41
Total Ca (g/kg)	38.44
Available Ca (g/kg)	6.1
Fe (mg/kg)	1187
Zn (mg/kg)	54
Cu (mg/kg)	3.7
Mn (mg/kg)	152.7

Table 2. Physical and chemical characteristics of the soil used in this study.

Parameters	Value
Sand (%)	95
Clay (%)	5
pH	7.72
C/N ratio	13
OC (g/kg)	10.4
N-total (g/kg)	0.8
NO_3^--N (mg/kg)	19.1
NH_4^+-N (mg/kg)	7
Available P (mg/kg)	24
Available K (mg/kg)	193
Available Ca (g/kg)	0.5
Zn (mg/kg)	0.4
Mn (mg/kg)	2
Fe (mg/kg)	24.5
Cu (mg/kg)	0.3

2.3. Soil Incubation Experiment

A 21-day incubation experiment was performed to determine the mineralization rates of the N, P, and Ca from the *G. sesquipedale* residue. An aliquot of the pre-sieved soil (25 g) was placed in a 100 ml bottle and mixed with 0, 0.14, 0.24, and 0.48 g of crushed *G. sesquipedale* residue (Table S1, provided in the Supplementary Materials). Three replicates of each treatment were prepared for each of the three sampling dates (day 0 before incubation, and 10 and 21 days after incubation) to permit destructive sampling for a total of 45 bottles. All bottles were brought to 18% gravimetric moisture, weighed, and incubated at 28 °C ± 2 under controlled conditions. Every three days, the bottles were weighed and distilled water was added as needed to maintain their initial weight. The moisture was determined using a moisture analyzer (model MOC63u, Shimadzu). The concentrations of the soil's available nutrients (NH_4^+-N, NO_3^--N, P, and Ca) were determined as described in Section 2.2.

2.4. Plant Growth Experiment

This experiment was conducted to evaluate the fertilizer value of the *G. sesquipedale* residues using two crops: strawberry (*Fragaria* × *ananassa*. Var. *Fortuna*) (for 195 days), and corn (*Zea mays* L. Var. Pioneer) (for 40 days). Both experiments were carried out in plastic pots in a greenhouse at an average temperature of 23 °C (minimum and maximum: 12 °C and 35 °C, respectively), with 200 mL of water irrigation every other day and under sunlight conditions, according to a completely randomized design with three replications.

For the strawberry experiment, seedlings were obtained from a commercial farm in the locality of Moulay Bouselham, Morocco in alveoli trays and transplanted into pots (38.4 cm diameter) containing 9 kg of the pre-sieved soil mixed with or without the *G. sesquipedale* residue. Each pot had one strawberry plant. The residue-treated pots received either 70 g (equivalent to 6 t ha^{-1}) or 210 g (18 t ha^{-1}) of the *G. sesquipedale* residue. The strawberry fruits were weighed five times (60, 90, 120, 150, and 195 days after fruit maturity). The leaf dry weight, number of leaves, number of branches, and number of fruits were recorded after 195 days of transplantation. At 90 days, the harvested strawberry fruits were dried at 70 °C to a constant weight for mineral analysis.

For the corn experiment, pots (6.4 cm diameter) were filled with 200 g of soil mixed with the *G. sesquipedale* residue at a rate of 0 g, 0.24 g, 1.24 g, and 2.48 g per pot, corresponding, respectively, to 0.8 t ha^{-1}, 4 t ha^{-1}, and 8 t ha^{-1}. All of the pots were seeded with seven seeds of corn, and one plant was maintained in each pot after germination.

The dry weight of the aboveground parts of the corn plants dried at 70 °C was determined 40 days after sowing. The minerals N, P, K, Ca, Mg, Fe, Mn, Zn, and Cu in the corn leaves, strawberry fruits, in the dry soils, and soils' OM after harvesting were determined according to the methods cited in Section 2.2.

2.5. Data Analysis

All statistical analyses were performed with SPSS version 22.0 (IBM, Armonk, NY, USA). The effect of the residue addition on the mineralization of N, P, and Ca and on the growth of the strawberry plants, on the growth of the corn plants, and on the nutrient contents in the strawberry fruit, in the corn leaves, and in the soils after harvesting was analyzed using ANOVA. The obtained means were compared using the Tukey test. In all cases, differences were considered statistically significant at $p < 0.05$.

3. Results

3.1. Release of N, P, and Ca from the G. sesquipedale Residue

3.1.1. N Release

There was a significant ($p < 0.05$) influence of the *G. sesquipedale* residues on NH_4^+-N release at 10 and 21 days of incubation and on NO_3^--N release at 21 days of incubation. NH_4^+-N was decreased in the control and in all the residue treatments after 10 days of incubation (Figure 1a). On the other hand, NO_3^--N increased over the incubation time in response to the application rates (Figure 1b).

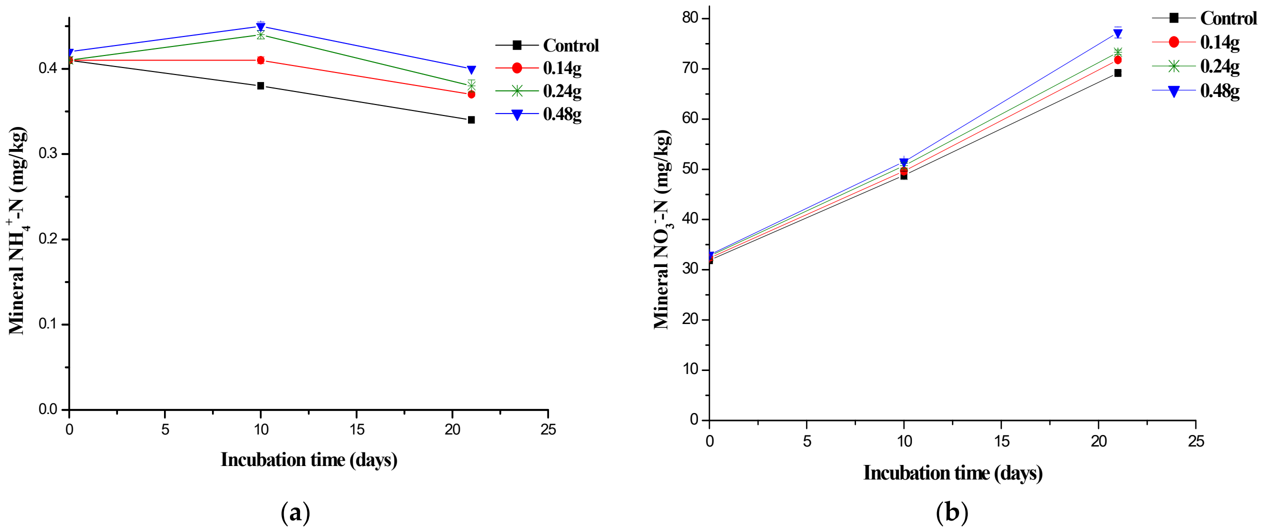

Figure 1. (**a**) Ammonium-N (NH_4^+-N) release and (**b**) nitrate–nitrogen (NO_3^--N) release affected by the residue applications (0.1 4 g, 0.24 g, and 0.48 g). The values are means (n = 3) and the error bars represent the standard errors.

At day 0, the NH_4^+-N contents in the soils were 0.41, 0.41, 0.41, and 0.42 mg kg^{-1} in soils treated with 0 g, 0.14 g, 0.24 g, and 0.48 g, respectively, while at 21 days, these values were 0.34, 0.37, 0.38, and 0.4 mg kg^{-1}, respectively.

NO_3^--N was increased gradually in the soils amended with the *G. sesquipedale* residues from 0 to 21 days of incubation. At 21 days of incubation, the maximum NO_3^--N in the soil reached 77.2 mg kg^{-1} (0.48 g), followed by 73.3 mg kg^{-1} (0.24 g) and 71.7 mg kg^{-1} (0.14 g).

3.1.2. P and Ca Release

The available P increased significantly ($p < 0.05$) during the incubation time. The highest amounts of available P released from the residue were recorded at the beginning of the experiment, with the highest residue rate being 0.48 g (58.38 mg·kg^{-1}), followed by 0.24 g (57.25 mg·kg^{-1}) and 0.14 g (56.97 mg·kg^{-1}) (Figure 2a).

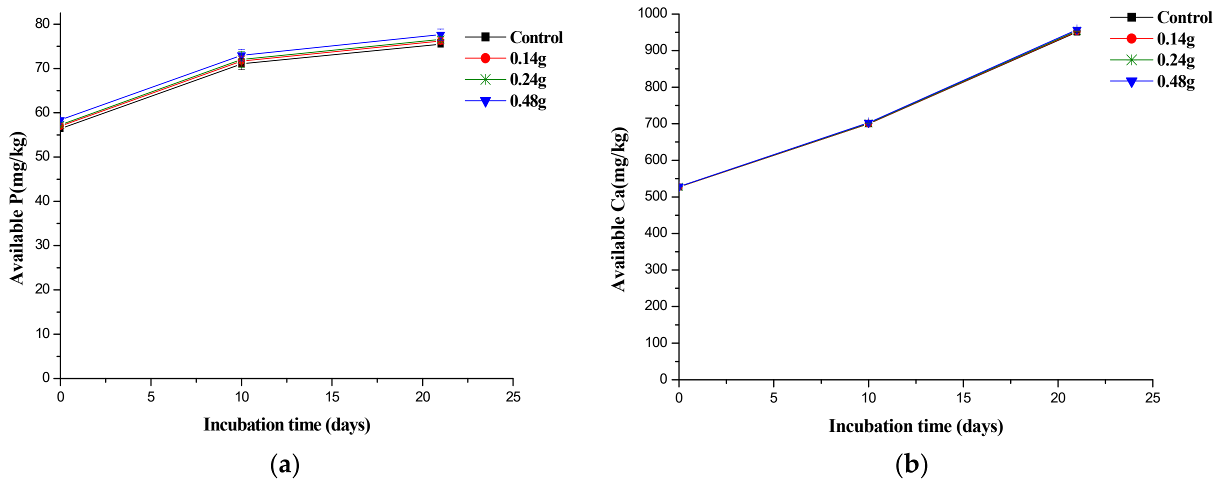

Figure 2. (**a**) Available phosphorus (P) and (**b**) available calcium (Ca) affected by the residue applications (0.14 g, 0.24 g, and 0.48 g). The values are means (n = 3) and the error bars represent the standard errors.

There was also a significant difference in the available Ca content at day 21 of the incubation period ($p < 0.05$). The available Ca gradually increased over the course of incubation. The highest release was observed with the highest rate of residue application (0.48 g (957 mg·kg^{-1}) (Figure 2b)).

3.2. Bio-Fertilization Effect of the G. sesquipedale Residue

3.2.1. Bio-Fertilization Effect of the Residue on the Strawberry Plants

The application of the *G. sesquipedale* residue to the soils significantly enhanced fruit weight at 90, 120, and 150 days. Both residue rates (6 and 18 t ha^{-1}) were similarly efficient in improving fruit weight (Table 3). Leaf dry weight and the number of leaves and fruits increased significantly at 195 days, proportionally to the residue rate used (Table 4).

Table 3. Fruit fresh weight of the strawberry plants grown in the soils amended with two different rates of the *G. sesquipedale* residue at five harvesting times (60, 90, 120, 150, and 195 days).

Residue Treatments	Fruit Fresh Weight (g/Plant)				
	60 Days	90 Days	120 Days	150 Days	195 Days
Control	16.0 ± 0.8 a	28.0 ± 1.7 a	25.6 ± 0.8 a	23.6 ± 0.8 a	20.8 ± 1.2 a
6 t ha^{-1}	17.2 ± 1.7 a	39.6 ± 0.9 b	34.2 ± 0.9 b	36 ± 1.3 b	22.8 ± 0.9 a
18 t ha^{-1}	17.6 ± 0.9 a	36.5 ± 1.6 b	32.6 ± 1.0 b	34.8 ± 1.3 b	23.2 ± 0.5 a

Data shown are means ± standard deviations (n = 3); values with different letters are significantly ($p < 0.05$) different according to the Tukey test.

Table 4. Leaf dry weight and number of leaves, branches, and fruits after the harvest of the strawberry plants grown in soils amended with different levels of the *G. sesquipedale* residue.

Residue Treatments	Leaf Dry Weight (g)	Leaf Number/Plant	Branches Number/Plant	Fruits Number
Control	93.8 ± 1.6 a	30 ± 0.6 a	9 ± 1.2 a	27 ± 0.7 a
6 t ha^{-1}	153.1 ± 2.1 b	37 ± 0.7 b	11 ± 1.0 a	35 ± 0.5 b
18 t ha^{-1}	171.0 ± 1.8 c	45 ± 0.5 c	12 ± 0.9 a	39 ± 1.0 c

Data shown are means ± standard deviations (n = 3); values with different letters are significantly ($p < 0.05$) different according to the Tukey test.

The addition of the *G. sesquipedale* residue enhanced the nutrient contents of the strawberry fruits. The increase was significant for N, Ca, Mn, Fe, and Zn. An increased rate of residue corresponded to increased concentrations of N (4.15 g kg^{-1}), Ca (3.97 g kg^{-1}), Zn (40.66 mg kg^{-1}), Mn (77.66 mg kg^{-1}), and Fe (92.66 mg kg^{-1}), though this was not the case for the P, K, Mg, and Cu concentrations, which did not differ significantly between the residue rates of 6 t ha^{-1} and 18 t ha^{-1} (Tables 5 and 6).

Table 5. Macro-elements in the fruits of the strawberry plants grown in soils amended with different levels of the *G. sesquipedale* residue.

Residue Treatments	Macro-elements (g/kg)				
	N	P	K	Ca	Mg
Control	3.31 ± 0.04 a	2.44 ± 0.17 a	5.55 ± 0.51 a	2.71 ± 0.14 a	1.02 ± 0.05 a
6 t ha^{-1}	5.60 ± 0.16 c	2.96 ± 0.14 a	6.94 ± 0.43 a	3.69 ± 0.25 b	1.52 ± 0.27 a
18 t ha^{-1}	4.15 ± 0.12 b	3.09 ± 0.39 a	7.06 ± 0.32 a	3.97 ± 0.10 b	1.58 ± 0.04 a

Data shown are means ± standard deviations (n = 3); values with different letters are significantly ($p < 0.05$) different according to the Tukey test.

Table 6. Micro-elements in the fruits of the strawberry plants grown in soils amended with different levels of the *G. sesquipedale* residue.

Residue Treatments	Micro-elements (mg/kg)			
	Mn	**Fe**	**Cu**	**Zn**
Control	38.66 ± 1.44 a	49.66 ± 1.20 a	1.66 ± 0.32 a	19.66 ± 1.44 a
6 t ha^{-1}	54.33 ± 1.20 b	91.00 ± 1.52 b	2.00 ± 0.00 a	31.00 ± 0.57 b
18 t ha^{-1}	77.66 ± 0.87 c	92.66 ±1.76 b	2.33 ± 0.32 a	40.66 ± 0.66 c

Data shown are means ± standard deviations (n = 3); values with different letters are significantly ($p < 0.05$) different according to the Tukey test.

3.2.2. Bio-Fertilization Effect of the Residue on the Corn Plants

The aboveground parts of the corn plants increased with the addition of the *G. sesquipedale* residue. This increase was significant at the rates of 4 t ha^{-1} and 8 t ha^{-1}, for which the plant biomass was raised, respectively, by 151 and 155% compared to the control treatment. The concentrations of N, P, Mg, and Fe were also increased significantly with the residue addition. Under the highest application rate (8 t ha^{-1}), the increase reached +58% for Mg, +40% for P, +38% for N, and +6% for Fe when compared to the control treatment (Tables 7 and 8).

Table 7. Dry weight of the aboveground parts of the corn, and the macro-elements in the leaves of the corn plants grown in soils amended with different levels of the *G. sesquipedale* residue.

Residue Treatments	Dry Weight (g)	Macro-elements (g/kg)				
		N (g/kg)	**P (g/kg)**	**K (g/kg)**	**Ca (g/kg)**	**Mg (g/kg)**
Control	0.51 ± 0.04 a	7.79 ± 0.46 a	1.89 ± 0.09 a	13.14 ± 0.01 a	0.45 ± 0.01 a	0.43 ± 0.01 a
0.8 t ha^{-1}	0.57 ± 0.07 a	9.00 ± 0.16 b	2.03 ± 0.08 ab	13.37 ± 0.24 a	0.51 ± 0.04 a	0.53 ± 0.02 ab
4 t ha^{-1}	1.28 ± 0.14 b	10.05 ± 0.00 c	2.61 ± 0.27 b	13.57 ± 0.12 a	0.51 ± 0.04 a	0.55 ± 0.01 ab
8 t ha^{-1}	1.3 ± 0.11 b	10.73 ± 0.04 d	2.65 ± 0.05 b	13.71 ± 0.12 a	0.52 ± 0.04 a	0.68 ± 0.04 b

Data shown are means ± standard deviations (n = 3); values with different letters are significantly ($p < 0.05$) different according to the Tukey test.

Table 8. Micro-elements in the leaves of the corn plants grown in soils amended with different levels of the *G. sesquipedale* residue.

Residue Treatments	Micro-elements (mg/kg)			
	Mn (mg/kg)	**Fe (mg/kg)**	**Cu (mg/kg)**	**Zn (mg/kg)**
Control	84.00 ± 1.99 a	191.66 ± 1.76 a	12.66 ± 0.87 a	31.33 ± 0.32 a
0.8 t ha^{-1}	90.33 ± 1.44 a	196.00 ± 2.30 abc	15.33 ± 1.85 a	36.66 ± 2.33 a
4 t ha^{-1}	90.66 ± 0.87 a	202.33 ± 1.44 bc	16.66 ± 0.32 a	37.00 ± 1.99 a
8 t ha^{-1}	91.00 ± 1.52 a	204.00 ± 2.51 c	17.33 ± 1.20 a	37.33 ± 120 a

Data shown are means ± standard deviations (n = 3); values with different letters are significantly ($p < 0.05$) different according to the Tukey test.

3.3. Soil Organic Amendment Effect of the G. sesquipedale Residue

3.3.1. Amendment Effect of the Residue on Soils Supporting the Strawberry Plants

The results revealed that some macro-elements, micro-elements, and OM increased significantly in the soils after the harvest of the strawberry plants.

The treatments enhanced the levels of nutrients (N and Ca) in the soil, and the maximum amounts of N (+169%), Ca (+192%), and OM (+152%) were recorded under the highest application rates of the residue in comparison to the control (Tables 9 and 10).

Table 9. Macro-element and organic matter (OM) contents in soils after the harvest of the strawberry plants receiving different levels of the *G. sesquipedale* residue.

Residue Treatments	Macro-elements (g/kg)					
	N	P	K	Ca	Mg	OM%
Control	0.67 ± 0.02 a	1.43 ± 0.23 a	1.26 ± 0.11 a	6.83 ± 0/76 a	1.77 ± 0.23 a	1.53 ± 0.06 a
6 t ha^{-1}	1.50 ± 0.00 b	1.45 ± 0.12 a	1.50 ± 0.15 a	15.60 ± 1.72 b	2.50 ± 0.24 a	2.98 ± 0.08 b
18 t ha^{-1}	1.80 ± 0.00 c	1.47 ± 0.14 a	1.46 ± 0.17 a	19.93 ± 1.18 b	2.36 ± 0.16 a	3.82 ± 0.05 c

Data shown are means ± standard deviations (n = 3); values with different letters are significantly ($p < 0.05$) different according to the Tukey test.

Table 10. Micro-element contents in soils after the harvest of the strawberry plants receiving different levels of the *G. sesquipedale* residue.

Residue Treatments	Micro-elements (mg/kg)			
	Mn	Fe	Cu	Zn
Control	199.00 ± 1.15	412.00 ± 1.15 a	12.67 ± 1.20 a	64.67 ± 0.87 a
6 t ha^{-1}	210.00 ± 1.52 b	425.67 ± 0.87 b	14.33 ± 0.32 ab	66.00 ± 0.57 ab
18 t ha^{-1}	214.00 ± 0.99 b	427.00 ± 0.57 b	16.67 ± 0.32 b	68.67 ± 0.66 b

Data shown are means ± standard deviations (n = 3); values with different letters are significantly ($p < 0.05$) different according to the Tukey test.

3.3.2. Bio-Fertilization Effect of the Residue on the Soils Supporting the Corn Plants

After harvesting the corn crops, the macro- and micro-elements (N, Ca, Mg, Mn, Fe, Zn, and Cu) and OM were increased significantly in the soils that received the residue treatments in comparison to the control. The residue enhanced the levels of N (+85%), Mg (+261%), and MO (+37%) in the soils under the highest application amounts of the treatment in comparison to the control (Tables 11 and 12).

Table 11. Macro-element and OM contents in soils after the harvest of the corn plants receiving different levels of the *G. sesquipedale* residue.

Residue Treatments	Macro-elements (g/kg)					OM%
	N (g/kg)	P (g/kg)	K (g/kg)	Ca (g/kg)	Mg (g/kg)	
Control	0.69 ± 0.01 a	1.43 ± 0.01 a	1.30 ± 0.01 a	11.20 ± 0.07 a	1.21 ± 0.02 a	1.64 ± 0.09 a
0.8 t ha^{-1}	0.86 ± 0.01 b	1.48 ± 0.04 a	1.31 ± 0.01 a	13.42 ± 0.25 b	1.39 ± 0.02 a	1.82 ± 0.03 ab
4 t ha^{-1}	1.07 ± 0.03 c	1.52 ± 0.04 a	1.34 ± 0.01 a	15.55 ± 0.62 c	3.91 ± 0.04 b	1.99 ± 0.01 bc
8 t ha^{-1}	1.28 ± 0.05 d	2.04 ± 0.28 a	1.35 ± 0.01 a	19.17 ± 0.42 d	4.37 ± 0.08 c	2.24 ± 0.07 c

Data shown are means ± standard deviations (n = 3); values with different letters are significantly ($p < 0.05$) different according to the Tukey test.

Table 12. Micro-element contents in soils after the harvest of the corn plants receiving different levels of the *G. sesquipedale* residue.

Residue Treatments	Micro-elements (mg/kg)			
	Mn (mg/kg)	Fe (mg/kg)	Cu (mg/kg)	Zn (mg/kg)
Control	480.33 ± 1.44 a	796.33 ± 1.76 a	14.00 ± 2.07 a	59.00 ± 1.52 a
0.8 t ha^{-1}	498.66 ± 2.18 b	807.66 ± 2.33 b	19.33 ± 0.87 ab	61.66 ± 1.20 a
4 t ha^{-1}	511.33 ± 1.44 c	867.66 ± 1.85 c	21.00 ± 0.57 b	73.66 ± 2.18 b
8 t ha^{-1}	515.66 ± 1.44 c	937.66 ± 1.44 d	26.00 ± 1.73 c	77.00 ± 1.52 b

Data shown are means ± standard deviations (n = 3); values with different letters are significantly ($p < 0.05$) different according to the Tukey test.

4. Discussion

The use of biological products enhances soil fertility and minimizes the corresponding environmental impact [36]. Algae play an important role in agriculture, and they can be employed as biofertilizers and soil stabilizers [37]. Our results demonstrated that the *G. sesquipedale* residue issued from agar-agar production could be a promising source of macro- and micro-nutrients. The chemical composition indicated that the residue had high concentrations of the major elements C, N, Ca, and P. It also had the potential to provide supplementary micronutrients such as Fe, Mn, and Zn.

In our experiment, soils mixed with the *G. sesquipedale* residue were highly enriched in available N (NH_4^+-N and NO_3^--N). Moreover, NH_4^+-N concentrations were reduced at the end of the incubation times with corresponding increases in the NO_3^--N concentrations. These results indicate that NH_4^+-N may be converted to NO_3^--N. Much higher NO_3^--N concentrations than NH_4^+-N concentrations indicated that the nitrification of NH_4^+-N proceeded more rapidly than its mineralization [38]. The increase in NO_3^--N release with increasing incubation times could be due to the transformation of N by microbial biomass and extracellular enzyme activities in the soil [39]. The process is split into two stages. Initially, bacteria (Nitrosomonas) convert NH_4^+-N into nitrite (NO_2^-), and after this transformation, other bacteria (Nitrobacter) convert the NO_2^- into NO_3^--N [40]. However, further experiments should be conducted to further assess the microbial community changes associated with this residue addition.

Phosphorus was available immediately after the residue application to the soil at the beginning of the experiment. Kwabiah et al. [41] suggested that the immediate P release could be due to the water-soluble P content in the plant materials. P was released progressively during the incubation times, showing that microorganisms can improve P availability through biochemical processes and extracellular enzymatic hydrolysis [42].

The available Ca release increased gradually over time, likely because Ca^{2+} is involved in the structural part of the organic component. Their release, therefore, depends more on biological activity than on leaching [43,44].

The one-time application of the *G. sesquipedale* residue to soil had an efficient fertilizing effect on the strawberry crop (at 195 days) by enhancing both plant growth and fruit weight. This effect may be due to the additional mineral elements that can affect plant growth parameters [45]. The minerals result from the transformation of organic compounds into inorganic ones by microbial biomass [46]. The transformation of organic residues occurs rapidly with lower initial C:N ratios [47]. Our organic residue, as characterized by a low ratio (C:N = 10.7), can lead to a release of available elements that can improve plant growth and yield. However, further experiments should be conducted that use isotope trackers (such as 15N and 31P) to assess the nutrient release from the residue and the transfer in the different soil pools (organic and inorganic).

The application of the residue increased the macro- and micro-elements (N, Ca, Zn, Fe, and Mn) in the strawberry fruits. This increase could have been affected by the uptake of minerals from the nutrient-rich substrate [48]. According to the incubation test, the residue enhanced the N mineralization and the Ca release in soil progressively during over the incubation time. Mohamed et al. [49] suggested that the N and Ca fertilization of strawberry plants leads to enhance plant growth and yield parameters. Singh et al. [50] observed that the application of micronutrients (Fe and Zn) increases the morphological parameters and yield of strawberry plants. Therefore, N, Ca, Fe, and Zn may be the most important elements that enhanced the plant growth and fruit weight of the strawberry plants in our experiment. Similar findings were indicated by El-Miniawy et al. [51], who showed that seaweed enhanced the vegetative growth characteristics and fruit weight in strawberry crops.

The *G. sesquipedale* residue also showed an important fertilizer effect on the dry weight of the aboveground parts of the corn plants at 40 days. The increase was proportional to the amount of residue added. A deficiency in minerals in the early stages of corn growth is a major factor limiting its yield [52]. The release of available P and NH_4^+-N at the beginning of the incubation experiment might be considered to have supplied nutrients to the plants for a short period. P and N fertilizers have a positive effect on corn biomass yield [53]. The mean content of N, P, Mg, and Fe in corn leaves was higher in the residue-fertilized plants, which may indicate an enhanced bioavailability of these nutrients from the residue after application. Gaj et al. [54] showed that there was a significant relationship between the nutritional status during the vegetation stage of the corn crop and plant biomass.

Dineshkumar et al. [55] observed similar results with the application of algae to soil, which increased the dry weight of corn.

The levels of some macro-elements (N and Ca), some micro-elements (Zn, Cu, Fe, and Mn), and OM increased significantly in soil after the harvest of the strawberry and corn plants, corresponding to treatments with the different rates of the *G. sesquipedale* residue. This may indicate that enhanced OM improves the macro- and micro-elements in soil. The increase of OM improves soil's water-holding capacity and nutrient levels [56]. According to Gerke [57], soil organic matter affects the nutrient storage of N and P in soil and the availability of Fe, Zn, and Cu to plants. The increase in OM in the treated soils may be due to the presence of polysaccharides, such as cellulose, that were found in the *G. sesquipedale* residue [58]. The polysaccharides may lead to an increase in the labile carbon fraction in soil [59]. Similar results were observed by Alobwede et al. [60], who showed that the application of algae to soil increased the amounts of nutrients and OM. Illera-Vives et al. [61] also observed a residual effect of algae added to soil.

5. Conclusions

The soils mixed with the *G. sesquipedale* residue were enriched with available P at the beginning of the incubation and showed increased NO_3^--N and available Ca over the incubation experiment. The conducted tests under greenhouse conditions showed that the residue-fertilized soils increased the growth and fruit weight of strawberry plants, and they enhanced the dry weight of the aboveground parts of the corn plants. The residue improved the macro- and micro-elements in strawberry fruits and corn leaves. After plant harvest, OM and some macro- and micro-elements increased in the soils, indicating the fertilizer value of the *G. sesquipedale* residue as an organic fertilizer and soil amendment and, thus, its ability to contribute to sustainable agriculture. A future comparison study of commercially available biofertilizers should be conducted to compare the residue potential of *G. sesquipedale*. The efficacy of the *G. sesquipedale* residue should be verified at the field scale and completed by arboriculture studies to determine the longest period of efficacy of the residue.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142114217/s1, Table S1: Residue mixed with soil at 0.14 g, 0.24 g, and 0.48 g.

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