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Mitigation of Greenhouse Gas Emissions from Agricultural Fields through Bioresource Management

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Abstract: Efficient bioresource management can alter soil biochemistry and soil physical properties, leading to reduced greenhouse gas (GHG) emissions from agricultural fields. The objective of this study was to evaluate the role of organic amendments including biodigestate (BD), biochar (BC), and their combinations with inorganic fertilizer (IF) in increasing carbon sequestration potential and mitigation of GHG emissions from potato (*Solanum tuberosum*) fields. Six soil amendments including BD, BC, IF, and their combinations BDIF and BCIF, and control (C) were replicated four times under a completely randomized block design during the 2021 growing season of potatoes in Prince Edward Island, Canada. An LI-COR gas analyzer was used to monitor emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) from treatment plots. Analysis of variance (ANOVA) results depicted higher soil moisture-holding capacities in plots at relatively lower elevations and comparatively lesser volumetric moisture content in plots at higher elevations. Soil moisture was also impacted by soil temperature and rainfall events. There was a significant effect of events of data collection, i.e., the length of the growing season (p-value ≤ 0.05) on soil surface temperature, leading to increased GHG emissions during the summer months. ANOVA results also revealed that BD, BC, and BCIF significantly (p-value ≤ 0.05) sequestered more soil organic carbon than other treatments. The six experimental treatments and twelve data collection events had significant effects (p-value ≤ 0.05) on the emission of CO_2. However, the BD plots had the least emissions of CO_2 followed by BC plots, and the emissions increased with an increase in atmospheric/soil temperature. Results concluded that organic fertilizers and their combinations with inorganic fertilizers help to reduce the emissions from the agricultural soils and enhance environmental sustainability.

Keywords: agricultural soils; biochar; biodigestate; greenhouse gas emissions; inorganic fertilizers

Citation: Khan, R.; Abbas, A.; Farooque, A.A.; Abbas, F.; Wang, X. Mitigation of Greenhouse Gas Emissions from Agricultural Fields through Bioresource Management. *Sustainability* **2022**, *14*, 5666. https://doi.org/10.3390/su14095666

Academic Editor: Christophe Waterlot

Received: 5 April 2022
Accepted: 5 May 2022
Published: 7 May 2022

1. Introduction

Major greenhouse gases (GHGs) that emit from agricultural fields include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). GHG emissions associated with agriculture can be offset through management practices that also increase soil carbon sequestration [1,2] through the selective use of type (organic and inorganic) and methods, e.g., bioresource management such as the only and mixed-use of organic and inorganic soil amendments [3].

Soil organic amendments include raw animal manures, processed waste to biodigestate, and biochar produced from various organic feedstocks. Raw animal manure naturally emits CH_4 and N_2O as it decomposes in a field, but once processed into digestate, its emissions capacity is controlled when used as a soil amendment. Biodigestate is a processed organic waste with nutrient-rich byproducts. Its amendment in the soil does not only help to fertilize the soil, but it can also reduce some GHG emissions. According to Bustamente et al. [4], amending biodigestate in the soil is one of the most efficient biological methods by which emissions of GHGs, especially CO_2, can be reduced. It also helps return soil organic matter (SOM) and reduces GHG emissions [5].

Biodigestate is one of the most efficient biological methods by which emissions of GHG, especially CH_4, can be reduced [6]. Traditional compost naturally emits GHGs, such as CO_2 and CH_4, as it decomposes in a field [7]. One of the proposed uses of biodigestate is to distribute it on agricultural fields as a soil conditioner and fertilizer [8]. This makes the production of digestate a potential means of recycling waste from various industries, including agriculture and sewage treatment. Biodigestate has been reported to replace inorganic fertilizer as an environmentally safe nutrient management practice [9–12].

Biochar is organic matter that has been pyrolyzed or roasted under low oxygen concentrations. The low amount of oxygen prevents the material from being burned, which helps maintain certain characteristics of the original biomass, such as its porous nature. The pores in the biochar help hold water and air in the soil, which is beneficial for plant health [13]. Several studies have confirmed the idea that biochar enhances plant growth [14,15]. Not only does biochar help hold in water and nutrients found in the soil, but it also provides its nutrients. Biochar maintains the nutrients that existed in the biomass before it was burned, although this combination of nutrients depends on the type of biomass that was utilized [13]. Agegnehu et al. [16] observed that a mixture of compost and biochar decreased soil emissions by 16–33% as compared to mineral fertilizer in a peanut field.

SOM, regardless of its source from biodigestate or biochar, is universally recognized as a major factor in evaluating the performance of agricultural management practices to promote sustainable agriculture [17]. Xue et al. [18] investigated the association between agricultural management practices and environmental factors including plant factors. Their results revealed that long-term management practices with different intensities had certain environmental impacts on soil and its properties. Diacono and Montemurro [19] concluded that the application of organic amendments, such as manure, municipal solid waste, crop residues, compost, sewage sludge, and manure, can increase SOM content up to 90%.

There are comprehensive studies on the effects of inorganic fertilizers on GHG emissions, but there are very few comprehensive studies on the mixed use of organic and inorganic soil amendment on GHG emissions. It was hypothesized that the use of organic amendments and their combination with inorganic amendments will help to reduce the emission of CO_2, CH_4, and N_2O from the agricultural fields. Therefore, the objective of this study was to evaluate the role of organic amendments including biodigestate, biochar, and their combinations with inorganic fertilizer in increasing carbon sequestration and mitigation of GHG emissions from potato fields, as potato is a major crop in the world and its cultivation requires extensive soil disturbance.

2. Materials and Methods

2.1. Study Site

This study was carried out in the experimental fields of Atlantic-Agri tech farms in New Glasgow near Charlottetown in Queens County of Prince Edward Island (Figure 1). It is in the central portion of the island, in the southwest of North Rustico surrounded by hills at the bank of the hunter river. This study field shares the coordinates of 46.38369° N latitude and 62 to 63.36226° W longitude. Its climate is mostly humid throughout the year because it is surrounded by the Atlantic Ocean. The winter season is usually long on the island, with shorter summers. During winters, the island has many snowy and blizzard storms from the Atlantic Ocean and the Gulf of Mexico. Springtime is usually a moderately cool time and helps to melt down the snow and ice, and summers are warm here. During summer in the day, temperature reaches 30 °C and above. Autumn on the island receives heavy rainfall. The soil type of this area is sandy loam; this soil is originally developed from forest soils. This land is suitable for potato cultivation on the island.

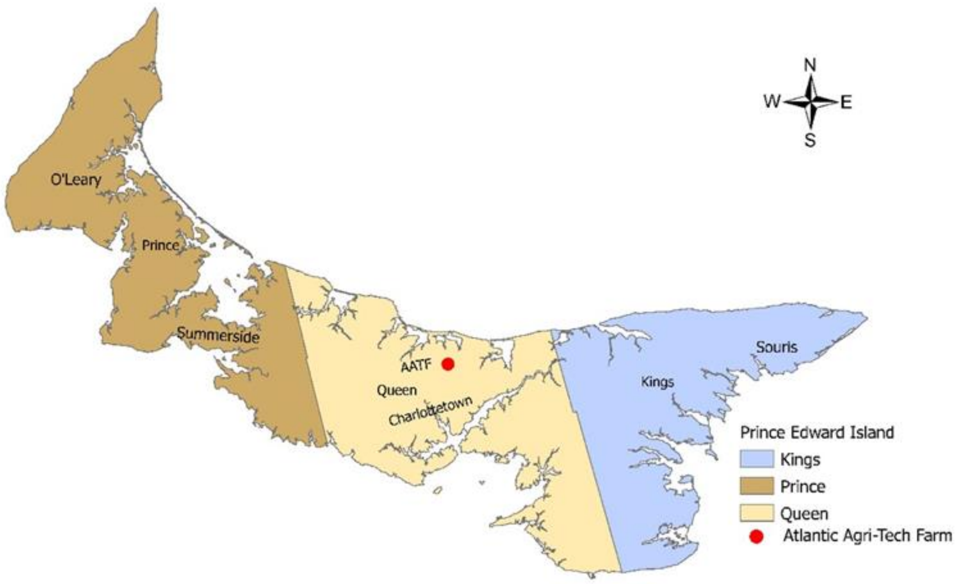


Figure 1. Map of Prince Edward Island. The red dot presents Atlantic-Agri tech farms in Queens County where the reported study was conducted.

2.2. Experimental Setup and Arrangements

Treatment plots (each 24 m^2) were developed to replicate the selected six treatments including biodigestate (BD), biochar (BC), inorganic fertilizer (IF), biodigestate + inorganic fertilizer (BDIF); biochar + inorganic fertilizer (BCIF), and control treatment without any amendment (C). The experimental treatments were replicated four times under a completely randomized block design. Selective chemical properties of the experimental field soil are given in Table 1.

Table 1. Properties of the soil of the experimental field used to make experimental plots.

Measured Elements	Values (ppm)	Measured Elements	Values (ppm)
Phosphorus	286	Zinc	1.2
Potash	141	Sulfur	20
Calcium	764	Manganese	30
Magnesium	714	Iron	16
Boron	0.3	Sodium	16
Copper	0.4	Organic matter	2.8%
pH	6.0	Soil type	Sandy loam

Biodigestate used in this experiment was produced from potato waste at the Cavendish facility. The biochar was produced from the feedstock of forest wood waste. The inorganic fertilizer was a combination of nitrogen, phosphorous, and potassium (i.e., commercially available Synthetic NPK fertilizer). The treatments BDIF was a mix of biodigestate and inorganic fertilizer, and BCIF was a mix of biochar and inorganic fertilizer. The mixed treatments were made by considering the chemical analysis of the biodigestate and biochar to account for the nutritional requirements of soil for potato production. The control treatment had no soil amendments. The application rate of each amendment was based on recommended N application for Russet Burbank as suggested by Prince Edward Island Potato Board researchers. The potato cut seeds (55–85 g) of the Russet Burbank variety of potatoes were sown 10 cm below the soil surface on 4 June 2021 in rows of 91 cm spacing with 40 cm spacing between the two seeds accommodating 15 seeds per row.

2.3. Monitoring of Soil Moisture Content, Soil Temperature and Gas Emissions

Water Scout SM100 soil moisture (Spectrum Technologies, Fort Worth, TX, USA) and soil temperature sensors (Spectrum Technologies, Fort Worth, TX, USA) were installed at each replication to monitor soil water content and soil temperature throughout the cropping season. All these sensors were attached with WatchDog Micro Station 1000 Series (Spectrum Technologies, Fort Worth, TX, USA) to log data every 30 min. Readings were logged onto dataloggers and downloaded on computers at fortnight intervals.

For monitoring greenhouse emissions, PVC (Polyvinyl Chloride)-made collars were permanently installed in each experimental plot for the duration of the growing season. Collars of the length of 10 cm (top 10 cm of the soil layer is considered important for CO_2 emission; therefore, the collars were inserted 5 cm deep into the soil leaving 5 cm of the same above ground) as practiced by Abbas and Fares [20]. The external diameter of the collar matched the inner diameter of the chamber of the Li-COR Trace Gas Analyzers (Lincoln, NE, USA) that was also used to measure soil temperature, in addition to concentrations of CH_4 and N_2O emissions, with an external sensor connected with Li-COR Trace Gas Analyzers. The software setup was needed to operate Li-COR Trace Gas Analyzer. The following steps were taken according to the following instructions of the manufacturer of the Li-COR Trace Gas Analyzer. The Li-COR Trace Gas Analyzer was used at the start of the growing season when plants had not emerged and multiple times during the growing season when plants had emerged.

2.4. Frequency of Greenhouse Gas and Other Data Collection

This activity included measurements of GHG emissions, during the whole growing season on a weekly and/or bi-weekly basis during the 2021 growing season of potatoes (Table 2). This database will be expanded with the help of data from future experiments. The idea is to build a historical database about greenhouse gas emissions from the soils of Prince Edward Island. Twelve events of GHG monitoring have been shown. These events spread during the growing season, and their sequence can be related to the temperature. For example, the events in the first and middle half of the growing season represent GHG emissions during higher temperatures, and the events toward the end of the growing season represent emissions during lower temperatures.

Table 2. Dates for monitoring greenhouse gas emissions and soil temperature during 12 events of 5 months throughout the 2021 growing season.

June	July	August	September	October
10	09	02	13	05
23	23	16	26	18
		23		29

2.5. Soil Organic Matter and Carbon Sequestration

Composite samples of soil were collected from 0–15 cm layer of each treatment plot on 4 June 2021 (at the time of seed sowing) and after harvesting (21 October 2021) to determine SOM using the method of loss on ignition [21]. The loss on ignition (LOI) tests were carried out at the soil laboratory of the Faculty of Sustainable Design Engineering of the University of Prince Edward Island using a muffle furnace (Model 550 Isotemp Series, Fisher Scientific, Hampton, NH, USA) and following the standard procedure [22]. Accordingly, 5 g of ground air-dried soil samples of <2 mm diameter were placed in 15 mL ceramic cups to oven-dry at 105 °C for 24 h. The oven-dried samples were cooled in a desiccator for a couple of hours before weighing them (M_{105}) for their mass. The samples (M_{105}) were then combusted for 5 h at 550 °C in the muffle furnace. The temperature of these samples was cooled to 105 °C before putting them in a desiccator. The cooled samples were weighed again (M_{550}) for their mass to determine the LOI [23] and thus SOM as:

$$\mathrm{LOI}(\%) = \left(\frac{M_{105} - M_{550}}{M_{105}}\right) \times 100$$

2.6. Statistical Analysis

Minitab 19 was used to perform the statistical analysis that included the analysis of variance (ANOVA) to test the significance of the six experimental treatments during the twelve events of data collection (Table 2) on SOM (as an indicator of carbon sequestration) and GHG emissions. Various assumptions, including normality test, constant variance, and independence of the error were tested at a 95% confidence interval. Therefore, the statistical means were considered significantly different at a p-value ≤ 0.05. Fisher's Least Significant Difference (LSD) was performed on data of field trials to separate means of significant difference.

3. Results and Discussion

3.1. Effect on Soil Moisture and Temperature

Analysis of the sample data depicted higher soil moisture-holding capacities in plots at relatively lower elevations (about 1 m determined from the relationship: $s = y/x$ where s is the slope, y is the average difference between the plot heights and x is the average distance between the two points in plots where the heights were measured) and comparatively lesser volumetric moisture content in plots at higher elevations (Figure 2). Soil moisture was also impacted by soil temperature and rainfall events as well. Soil moisture could have also been impacted by experimental treatments. The data of soil temperature measured across the experimental plots and along the growing season were therefore analyzed for this purpose.

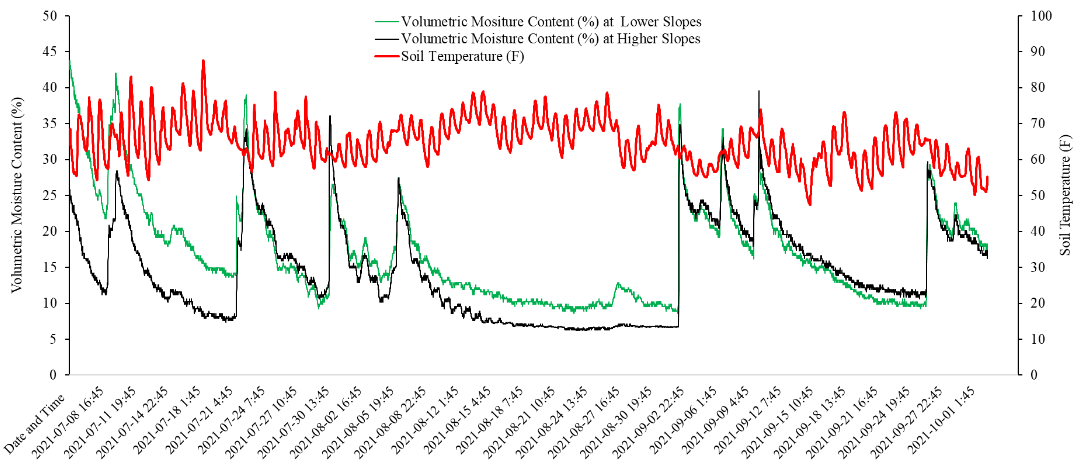


Figure 2. Variations in soil volumetric moisture content in treatment plots of low and high elevations, and soil temperature across the growing season.

There was a nonsignificant effect (p-value > 0.05) of experimental treatments and a significant effect of events of data collection, i.e., the length of the growing season (p-value ≤ 0.05) on soil surface temperature (Table 3). The seasonal effect of temperature might have dominated the individual effect of experimental treatments on the surface temperature of amendment plots [24,25] as depicted in Figure 3. Contemporary researchers have focused on elucidating the impact of biochar on soil thermal properties. For example, Zhao et al. [24] found that biochar can lower the temperature, and its addition to soil can significantly decrease soil temperature and thus thermal diffusive activity. Xiong et al. [25] suggested that the application of biochar at a medium dose can mitigate soil temperature fluctuation under high soil surface temperature conditions.

Table 3. Analysis of variance (ANOVA) results for the effect of experimental treatments and the twelve data collection events on the surface temperature of treatment plots (°C).

Source	DF	Adjusted SS	Adjusted MS	F Value	*p*-Value
Effect of six experimental treatments					
Treatments	5	7.04	1.409	0.08	0.996
Error	282	5203.97	18.454		
Total	287	5211.01			
Effect of twelve data collection events					
Season	11	4412.4	401.123	138.62	0.000
Error	276	798.7	2.894		
Total	287	5211.0			

DF: degree of freedom, SS: sum of squares, MS: mean of squares. Treatment means were considered significantly different at a p-value ≤ 0.05 (95% confidence interval).

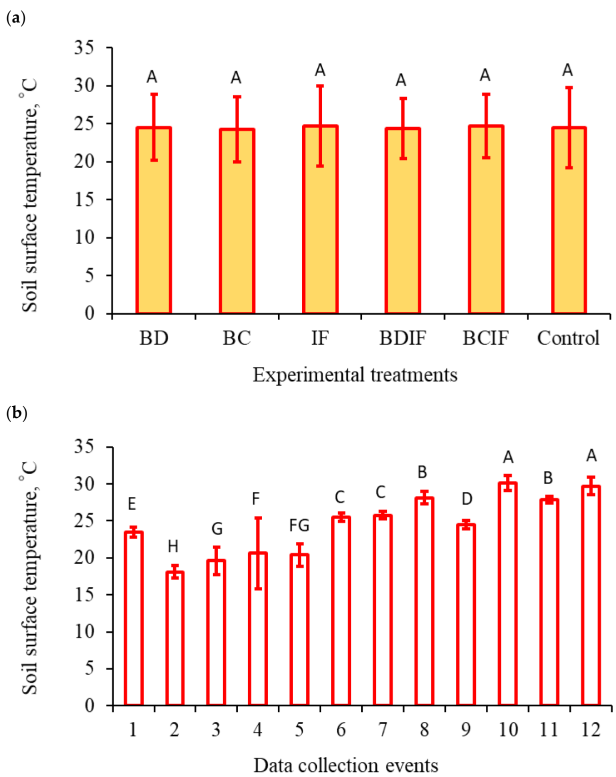


Figure 3. Mean values and standard deviation from means showing (**a**) the effects of soil amendments including biodigestate (BD), biochar (BC), inorganic fertilizer (IF), biodigestate + inorganic fertilizer (BDIF), biochar + inorganic fertilizer (BCIF), and control with no soil amendment and (**b**) the effect of soil amendments determined during twelve events of data collection throughout 2021 growing season on the surface temperature of treatment plots. The significantly different means have been separated and labeled with Fishers' Least Significant Difference (LSD) letters. The means labeled with similar LSD letters are not significantly different from one another.

3.2. Organic Matter and Carbon Sequestration from Experimental Treatments

Soil organic matter varied significantly (p-value ≤ 0.05) when measured just after soil amendment applications and at the end of the growing season (Table 4). This reflects interrelation and thus interdependence of the important soil health indicator, i.e., SOM on soil amendments. The importance of biodigestate and biochar thus becomes important to explore for improving soil health, carbon sequestration potential of the organic amendments, environmental safety, and tuber yield from agricultural fields in Prince Edward Island.

Table 4. Analysis of variance (ANOVA) results for the effect of experimental treatments on soil organic matter contents determined just after applying soil amendments and after harvesting plots.

Source	DF	Adjusted SS	Adjusted MS	F Value	*p*-Value
Just after applying soil amendments					
Treatments	5	2.713	0.5427	5.20	0.004
Error	18	1.880	0.1044		
Total	23	4.593			
After harvesting crop					
Treatments	5	5.267	1.0534	7.80	0.000
Error	18	2.432	0.1351		
Total	23	7.700			

DF: degree of freedom, SS: sum of squares, MS: mean of squares. Treatment means were considered significantly different at a p-value ≤ 0.05 (95% confidence interval).

From the *p*-values, it is evident that the significant effect of soil amendments on SOM was nominal at the time of amendment applications and became obvious towards the end of the growing season (Figure 4). At the beginning of the growing season, BDIF had significantly lower SOM than the other experimental treatments (Figure 4a). However, towards the end of the growing season, BD, BC, and BCIF treatments had significantly higher enhancement in SOM contents than the other treatments (Figure 4b).

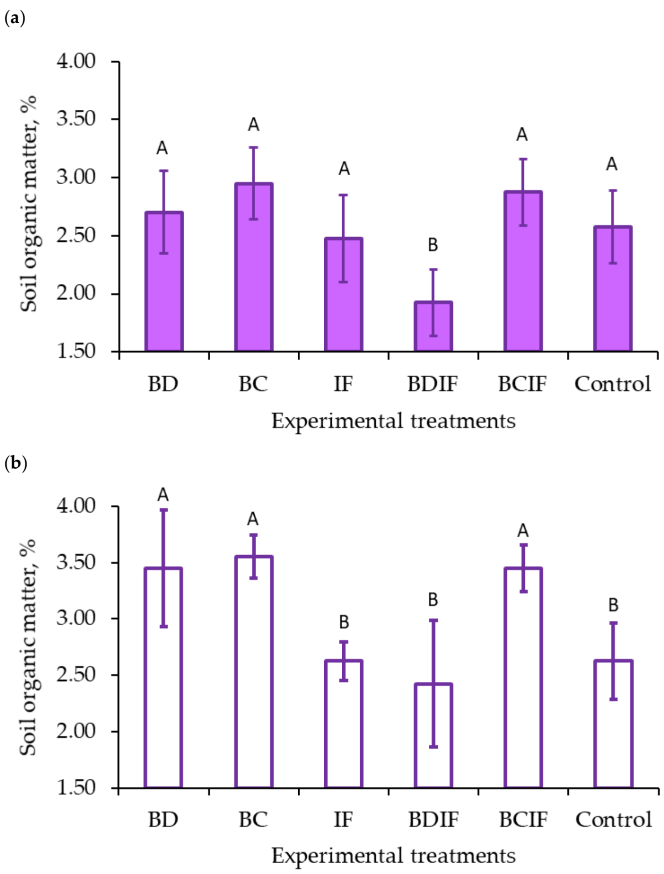


Figure 4. Mean values and standard deviation from means of soil organic matter in the soil samples collected (**a**) just after applying soil amendments and (**b**) after harvesting potatoes from experimental treatment plots of biodigestate (BD), biochar (BC), inorganic fertilizer (IF), biodigestate + inorganic fertilizer (BDIF), biochar + inorganic fertilizer (BCIF), and control with no soil amendment. The significantly different means have been separated and labeled with Fishers' Least Significant Difference (LSD) letters. The means labeled with similar LSD letters are not significantly different from one another.

These results implied that BD, BC, and BCIF treatments showed a significantly higher response in sequestering the highest organic carbon (implied from SOM values) in the soil. As a result, the nutrient management involving organic amendments of biochar, biodigestate, and a mixture of biochar with inorganic fertilizer can significantly enhance carbon sequestration in agriculture soils. Similar findings have been reported in the literature. For example, the study conducted by Cardelli et al. [26] revealed that the residual materials from waste such as biodigestate and biochar enrich the soil by sequestering carbon into the soil. Alburquerque et al. [27] also reported that the addition of biodigestate helps to make organic matter easily available to the plant, and it also enhances the soil organic matter.

Adding treatments like biochar and biodigestate helps to alleviate soil compaction. Biochar has the potential to soften the soil and increase fertility status [28]. Biochar has a great impact on the bulk density of the soil. It has a direct relationship with the bulk density, and adding biochar to the soil helps to decrease the soil bulk density. Bulk density has an indirect relation with soil porosity and a direct relation with soil compaction; the higher the bulk density is, the lower the soil porosity will be, and it will cause compaction. As biochar helps to reduce bulk density, it also reduces the compaction level in the soil [29]. Soil compaction is a major problem in agricultural soils due to heavy equipment used for tilling agricultural fields, and it is recognized that compaction not only disturbs the soil fertility and its structure but also increases the emissions of GHGs from the soil [30].

From an environmental perspective, one of the greatest benefits of biochar is its ability to store carbon in the soil. Charcoal is one of the most stable carbon compounds, which means that it takes a long time for it to degrade [13]. This contrasts with regular compost, which is quickly consumed by soil microorganisms and converted into carbon dioxide and methane [31]. This makes biochar a long-term method of sequestering carbon into the soil—the carbon that would otherwise be quickly lost as greenhouse gases into the atmosphere. Leading researchers on the sustainability of biochar have declared that "annual net emissions of carbon dioxide (CO_2), methane, and nitrous oxide could be reduced by a maximum of 1.8 Pg CO_2-C equivalent (CO_2-C_e) per year (12% of current anthropogenic CO_2-C_e emissions; 1 Pg = 1 Gt), and total net emissions over a century by 130 Pg CO_2-C_e, without endangering food security, habitat, or soil conservation" [32].

3.3. Trends in the Emission of Greenhouse Gases

The experimental treatments and data collections events had significant effects (p-value ≤ 0.05) on the emission of CO_2 (Tables 5 and 6). The plots amended with inorganic fertilizer had the highest emission of CO_2 followed by the plots of biodigestate and biochar when mixed with inorganic fertilizer (Figure 5a). However, the pure biodigestate-amended plots had the least emissions of CO_2 followed by the purely biochar-amended plots. These results are in concurrence with the findings reported in the literature. For example, Cardelli et al. [26] has reported that biochar and biodigestate and their combinations can reduce the CO_2 emissions from agricultural soils.

Table 5. Analysis of variance (ANOVA) results for the effect of experimental treatments on emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) from treatment plots.

Source	**DF**	**Adjusted SS**	**Adjusted MS**	**F Value**	***p*-Value**
CO_2 emissions, µmol/mol					
Treatments	5	11,614	2322.7	4.30	0.001
Error	282	152,260	539.9		
Total	287	163,873			
CH_4 emissions, µmol/mol					
Treatments	5	0.3730	0.074606	56.59	0.000
Error	282	0.3718	0.001318		
Total	287	0.7448			
N_2O emissions, µmol/mol					
Treatments	5	0.1278	0.025554	71.99	0.000
Error	282	0.1001	0.000355		
Total	287	0.2279			

DF: degree of freedom, SS: sum of squares, MS: mean of squares. Treatment means were considered significantly different at a p-value ≤ 0.05 (95% confidence interval).

Table 6. Analysis of variance (ANOVA) results for emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) from treatment plots monitored during twelve events of data collection throughout the growing season of 2021.

Source	**DF**	**Adjusted SS**	**Adjusted MS**	**F Value**	***p*-Value**
CO_2 emissions, µmol/mol					
Season	11	26,775	2434.1	4.90	0.000
Error	276	137,098	496.7		
Total	287	163,873			
CH_4 emissions, µmol/mol					
Season	11	0.07526	0.006842	2.82	0.002
Error	276	0.66956	0.002426		
Total	287	0.74482			
N_2O emissions, µmol/mol					
Season	11	0.01264	0.001149	1.47	0.141
Error	276	0.21523	0.000780		
Total	287	0.22787			

DF: degree of freedom, SS: sum of squares, MS: mean of squares. Treatment means were considered significantly different at a p-value ≤ 0.05 (95% confidence interval).

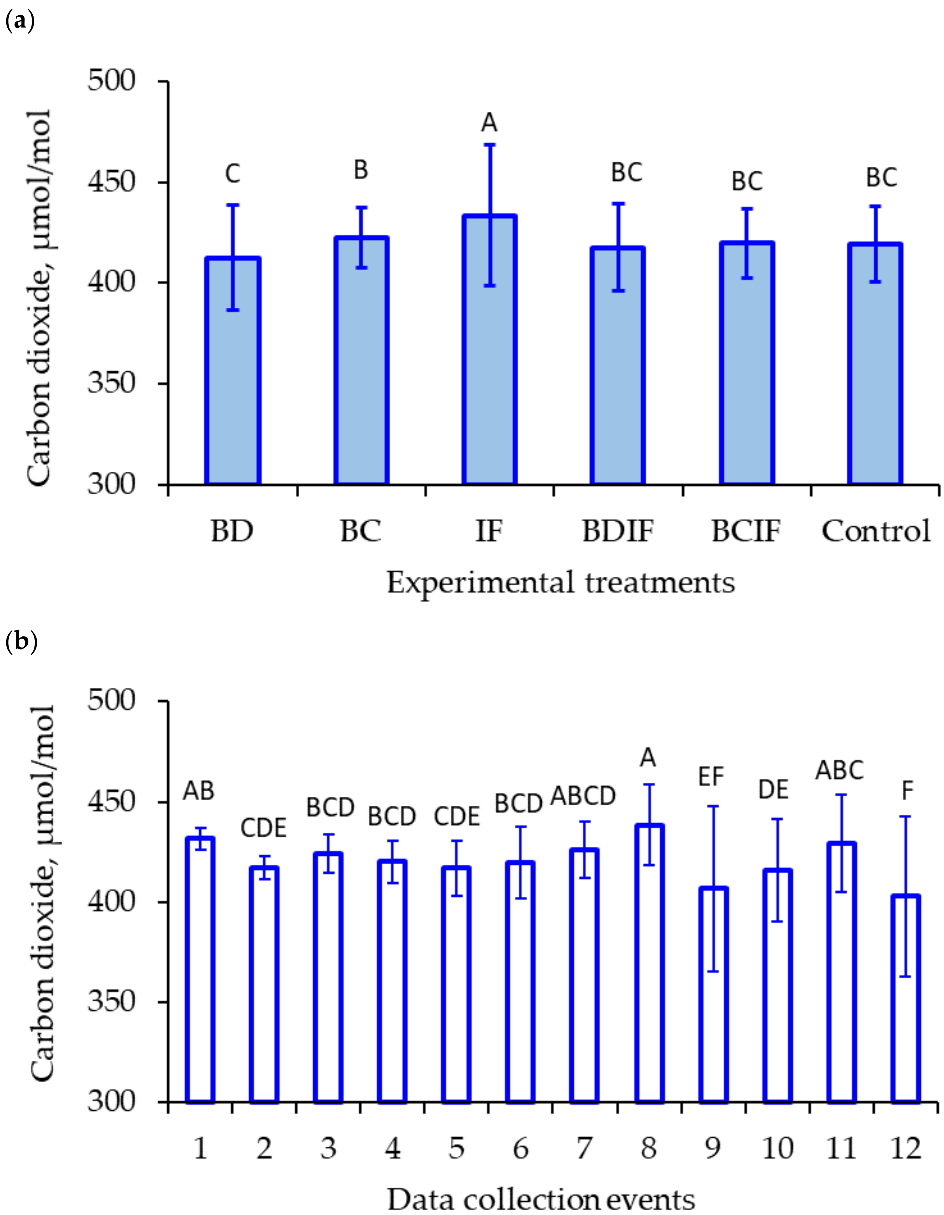
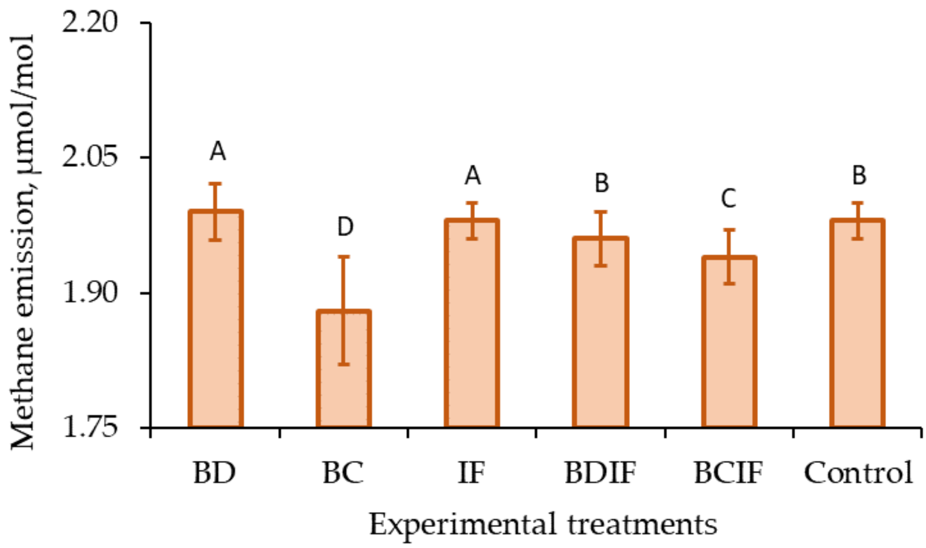


Figure 5. Mean values and standard deviation from means showing (**a**) the effects of soil amendments including biodigestate (BD), biochar (BC), inorganic fertilizer (IF), biodigestate + inorganic fertilizer (BDIF), biochar + inorganic fertilizer (BCIF), and control with no soil amendment and (**b**) the effect of soil amendments determined during twelve events of data collection throughout 2021 growing season on the emission of carbon dioxide from treatment plots. The significantly different means have been separated and labeled with Fishers' Least Significant Difference (LSD) letters. The means labeled with similar LSD letters are not significantly different from one another.

With an increase in temperature during the growing season, there was higher CO_2 emission during the summer months of June, July, and August than during the colder months of the growing season, reflecting a significant effect of the data collection events and thus temperature on CO_2 emission (Table 5 and Figure 5b). The least CO_2 emissions were recorded on 29 October 2021 (Figure 5).

Emissions of CH_4 experienced a significant effect (p-value ≤ 0.05) of experimental treatments (Table 5) and the events of data collection (Figure 6). The biochar amendment treatment had the lowest emission of CH_4 followed by the treatment of biochar's combination with inorganic fertilizer (Figure 6a). Biodigestate and inorganic fertilizer treatments had the highest emissions of CH_4. Thus, the biochar amendment was the best treatment among all other treatments to emit the least amount of CH_4 from the soil. In one of the reports, it is suggested that biochar is the most valuable source to reduce greenhouse gas emissions. It is pertinent to mention that CH_4 is 25 times more potent than CO_2 at trapping heat in the atmosphere; therefore, biochar helps to reduce the greenhouse gas effect on the atmosphere which is useful in mitigating climate change impact through the sustainable approach of agricultural practices [33].

(**a**)



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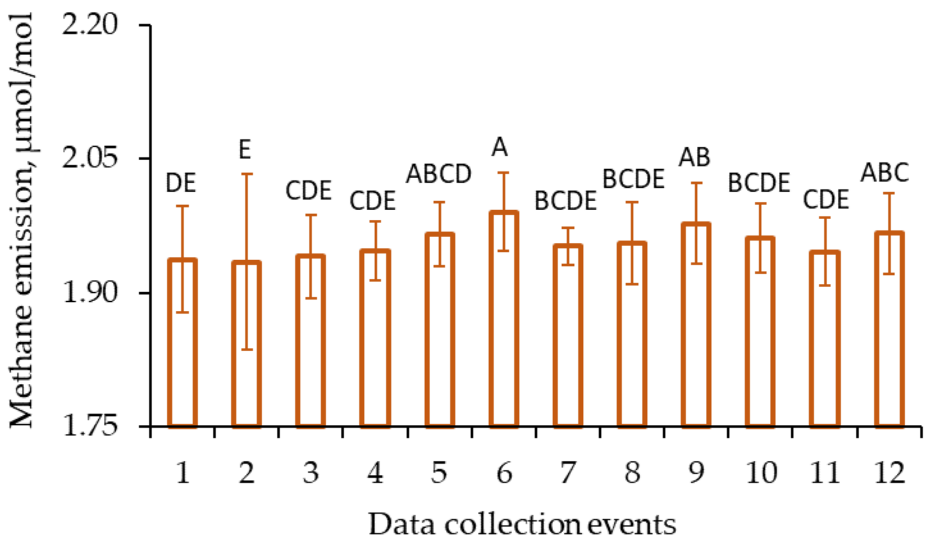

Figure 6. Mean values and standard deviation from means showing (**a**) the effects of soil amendments including biodigestate (BD), biochar (BC), inorganic fertilizer (IF), biodigestate + inorganic fertilizer (BDIF), biochar + inorganic fertilizer (BCIF), and control with no soil amendment and (**b**) the effect of soil amendments determined during twelve events of data collection throughout 2021 growing season on the emission of methane from treatment plots. The significantly different means have been separated and labeled with Fishers' Least Significant Difference (LSD) letters. The means labeled with similar LSD letters are not significantly different from one another.

Like on CO_2 emissions, the events of data collection/GHG monitoring and thus temperature had a significant effect causing treatment plots to emit the least amount of CH_4 emission during colder months, i.e., September and October (Figure 6b). Biochar has been recommended in the literature as a soil amendment to improve soil fertility and CH_4 emissions from rice cultivation [34].

There was a significant effect (p-value ≤ 0.05) of experimental treatments and a nonsignificant effect (p-value > 0.05) of data collection events on the emission of N_2O (Tables 5 and 6). The biochar amendment treatment had the lowest emission of N_2O followed by the control treatment (Figure 7a). Inorganic fertilizer and its mixture with biodigestate had the highest emissions of N_2O from their respective treatment plots. Thus, the biochar amendment was the best treatment among all other treatments to emit the least amount of N_2O from the soils amended with it.

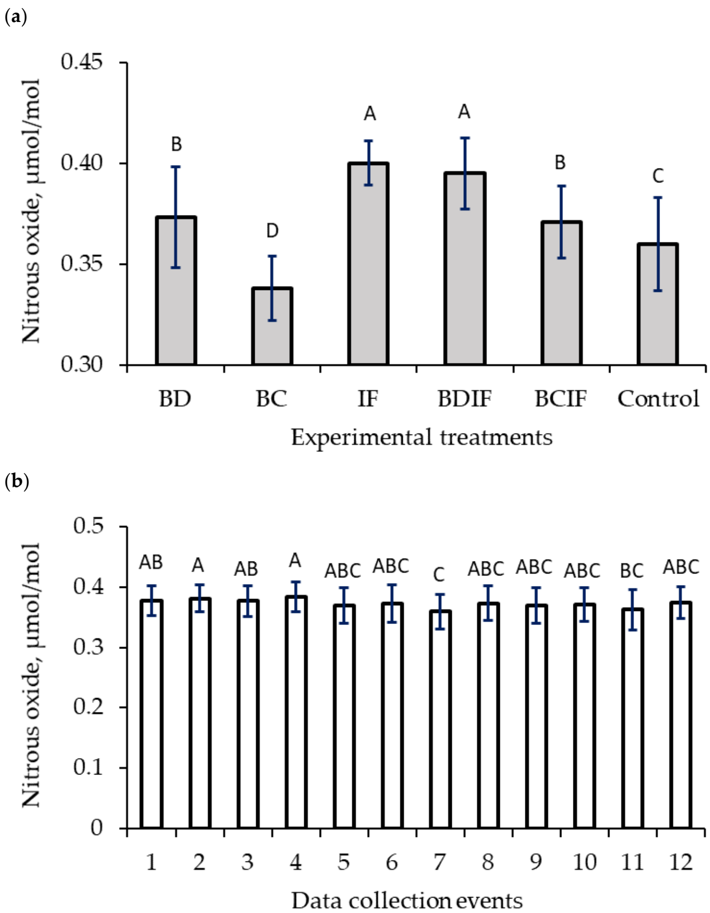

Figure 7. Mean values and standard deviation from means showing (**a**) the effects of soil amendments including biodigestate (BD), biochar (BC), inorganic fertilizer (IF), biodigestate + inorganic fertilizer (BDIF), biochar + inorganic fertilizer (BCIF), and control with no soil amendment and (**b**) the effect of soil amendments determined during twelve events of data collection throughout 2021 growing season on the emission of nitrous oxide from treatment plots. The significantly different means have been separated and labeled with Fishers' Least Significant Difference (LSD) letters. The means labeled with similar LSD letters are not significantly different from one another.

It is generally accepted that biochar application to soil may benefit both crop and soil productivity [35–37]. However, the literature has also reported increased GHGs emissions, especially CH_4 emissions [38,39]. Further, Zhang et al. [35] reported that biochar application promoted higher emissions of CH_4 from rice cultivation by an average of 45.9%. Xie et al. [40] demonstrated that biochar amendment reduced rice grain yield by an average of 24.8%. The effects of biochar are, in fact, dependent on soil type [40,41], feedstock type, biochar production conditions [39–42], and application rate [38,43]. Feng et al. [41] showed that the same biochar feedstock, pyrolyzed at different temperatures, resulted in varying CH_4 mitigation effects in different soils.

Like on CO_2 and CH_4 emission trends, the events of data collection/GHG monitoring and thus temperature had a significant effect causing treatment plots to emit the highest amount of N_2O during the hotter month than during colder months (Figure 7b). Although CH_4 and N_2O emissions are way smaller than CO_2, they are more potent than CO_2 and have multiple times more capacity to deteriorate the environment than CO_2 [41].

Figure 8 presents monthly means (averaged for two events of data collection in June, July, and September and three events of data collection during August (Table 2) of GHGs emissions from experimental plots during the first four months of the 2021 potato growing season. It is pertinent to mention here that regardless of the data collections events, biochar and biodigestate and their combinations with inorganic fertilizer had lower emissions as compared with emissions from the control or the only inorganic fertilizer treatments. The same was true for CO_2 (Figure 8a), CH_4 (Figure 8b), and N_2O (Figure 8c).

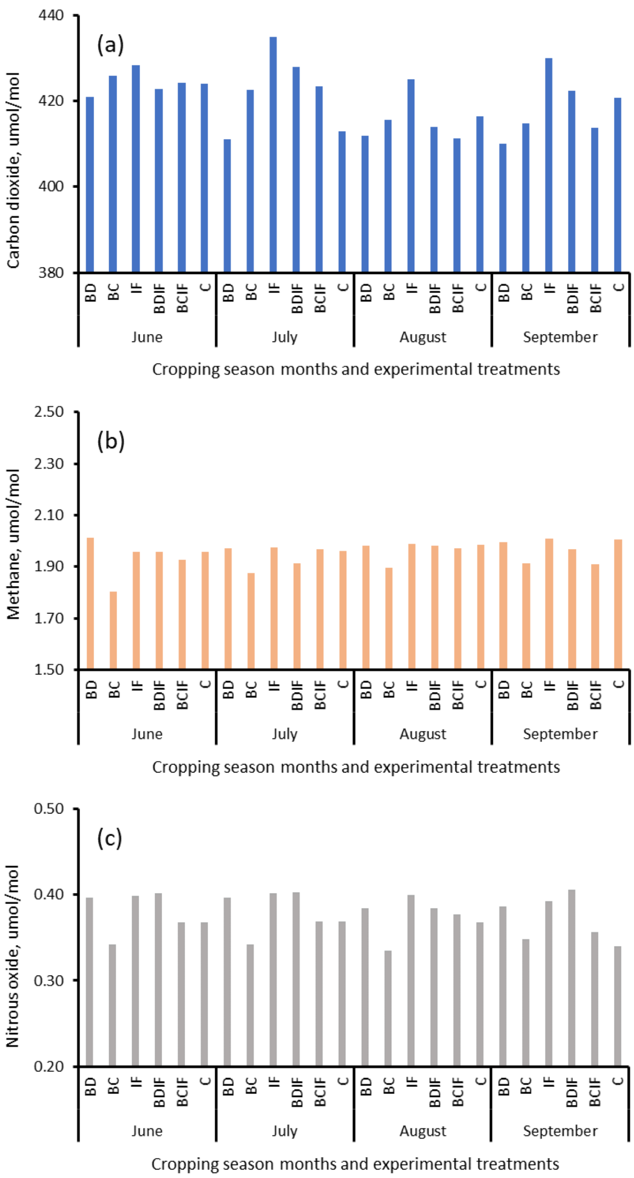

Figure 8. Monthly means of emissions of (**a**) carbon dioxide, (**b**) methane, and (**c**) nitrous oxide from experimental treatments including biodigestate (BD), biochar (BC), inorganic fertilizer (IF), biodigestate + inorganic fertilizer (BDIF), biochar + inorganic fertilizer (BCIF), and control with no soil amendment (C) collected during June, July, August, and September months of the 2021 potato growing season.

Several previous studies have illustrated the value of biochar in sequestering carbon [44,45]. Lefebvre et al. [45] modeled the potential of storing carbon through the production of biochar from sugarcane residues, concluding that this could reduce carbon dioxide emissions in the area under study by up to 31%. It would also greatly increase the carbon content of agricultural soils, improving crop health. Mona et al. [46] identified the benefits of utilizing microalgae as a feedstock for biochar production, explaining that microalgae can further reduce emissions by absorbing carbon from thermal power plants. In their 2015 study, Agegnehu et al. [16] observed that a mixture of compost and biochar decreased soil emissions by 16–33% as compared to mineral fertilizer in a peanut field. Another study showed that turning one tonne of crop residue into biochar could help sequester 920 kg of carbon dioxide [47].

To better understand the trend of GHG emissions and to relate the emissions with temperature and experimental treatments, CO_2 emissions during June, July, August, and September 2021 have been plotted against the six experimental treatments in Figure 9. The month of August had higher CO_2 emissions than the other months maybe because of higher atmospheric/soil temperature. It is understood that organic amendments had kept soil temperature low during the comparatively hotter month, such as August. For all ranges of temperature (during the four months of monitoring), CO_2 emission from inorganic fertilizer treatment was higher than all other treatments. In other words, organic fertilizers (i.e., biodigestate and biochar) and their combinations with inorganic fertilizers as well as control had significantly mitigated CO_2 emissions.

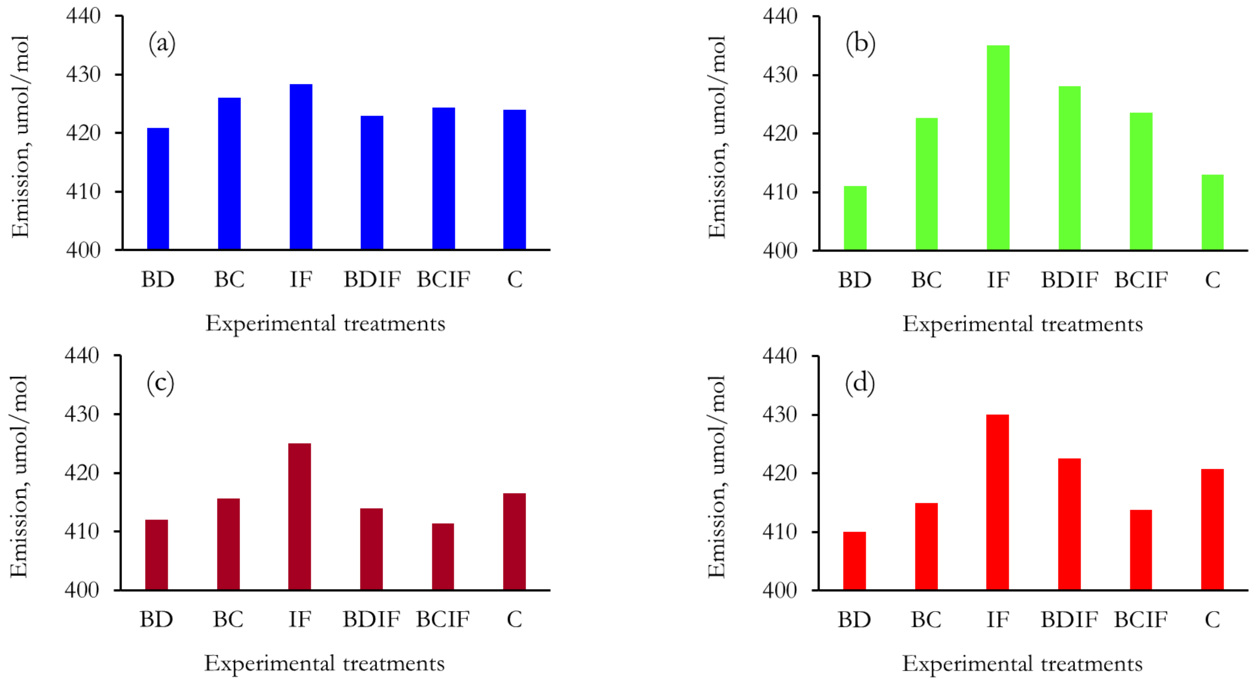

Figure 9. Monthly means of emissions of carbon dioxide during (**a**) June, (**b**) July, (**c**) August, and (**d**) September 2021 from experimental treatments including biodigestate (BD), biochar (BC), inorganic fertilizer (IF), biodigestate + inorganic fertilizer (BDIF), biochar + inorganic fertilizer (BCIF), and control with no soil amendment (C).

Biochar is beneficial if the soil is very acidic, but if the soil is at a more optimum pH—or if the crops being grown, such as blueberries, prefer acidic soils—too much biochar can upset this balance as reported by Cox [13] who recommends using ~2.5 cm of biochar for regular soil or up to ~5 cm of biochar for poor/compacted soil to avoid this issue. Moreover, a soil's pH level influences biochar's effectiveness in storing carbon; more acidic soils induce more rapid decomposition of the biochar, leading to an increase in CO_2 emissions. However, biochar's capacity to raise soil pH helps offset this issue [48].

3.4. Effect of Amendments on Soil Microorganisms

Although the physical data was not collected, it is important to discuss the effect of carbon levels produced from various experimental treatments on soil organisms and ultimately on plant growth. Biochar is reported to alter soil microbial populations and their activities [49–51]. Britniky et al. [49] conducted a three-year experiment to investigate the interactive effects of biochar soil amendment mixed with NPK and cattle manure, on microbial biomass carbon, soil dehydrogenase activity, and soil microbial community abundance in luvisols of arable land in the Czech Republic. They found that the co-application of biochar with manure changes soil properties in favor of increased microbial biomass and their activity. Biochar provides better aeration, improved water content in soils, plant nutrition, and a boost to plant cultivation [52–55]. Increasing plant nutrients sourced from biochar can help improve plant cultivation [56]. Abbas et al. [15] evaluated the effect of the application of biochar in combination with the recommended synthetic fertilizer on soil properties, maize (*Zea mays* L.) plant growth characteristics, and maize grain yield and quality parameters, and they concluded that the potential of biochar application in combination with nitrification inhibitor may be used as the best nutrient management practice for enhanced soil fertility and crop yield.

Many environmental factors including solar radiation, temperature, precipitation, and atmospheric greenhouse gas emissions have huge impacts on crop cultivation and soil organisms; therefore, an optimal plant cultivation environment would require an intricate balance of all these components [57]. However, due to climate change and greenhouse gas mitigation, this is not always the case, as we observe elevated levels of CO_2 in the atmosphere [57,58]. A study conducted by He et. al. [58] used phylogenetic microarrays (PhyloChip) to assess the effects of elevated CO_2 on the nature of soil for plant cultivation and soil microbial communities. With regards to the nature of the soil, some of the changes they observed with elevated CO_2 included an increase in plant biomass, a decrease in the aboveground N concentration, increased soil pH, and an increase in soil moisture. They also examined the richness of soil microbial communities, determined by several operational taxonomic units (OTUs), to investigate the impact of elevated CO_2 on soil microorganisms. Their findings revealed lower numbers of OTUs at elevated CO_2, suggesting that the richness of soil microbial communities was decreased, proposing a shift in microbial community composition at higher levels of CO_2. Additionally, higher levels of CO_2 also show increased activity of enzymes present in the soil [59].

4. Conclusions

Extensive and conventional agricultural operations deteriorate soil health and enhance greenhouse emissions. Research activities were performed during the 2021 growing season at Atlantic Agri-Tech Farm, Hunter River, New Glasgow region of Prince Edward Island to evaluate the role of locally produced biodigestate and biochar and their combination with inorganic fertilizer on the enhancement of SOM and mitigation of GHG emissions. The individual and combined effect of organic and inorganic soil amendments was seen in SOM enhancement and reduction in GHG emissions. ANOVA results depicted higher soil moisture-holding capacities in plots at relatively lower elevations and comparatively lesser volumetric moisture content in plots at higher elevations. Soil moisture was also impacted by soil temperature and rainfall events. Significant variations in SOM were also recorded when measured just after soil amendment application and at the end of the growing season, reflecting inter-relation and thus interdependence of this important soil health indicator on soil organic amendments. These results implied that biodigestate, biochar, and the mixed treatment of biochar + inorganic fertilizer showed a significantly higher response in sequestering the highest organic carbon in the soil. GHG emissions varied significantly among the six experimental treatments and during the twelve data collections events during the growing season. The plots amended with inorganic fertilizer had the highest emission of CO_2 followed by the biodigestate and biochar plots when mixed with inorganic fertilizer. However, the pure biodigestate-amended plots had the least emissions of CO_2 followed by the purely biochar-amended plots. Therefore, it can be concluded that the GHGs had varying emissions that depended on the interaction of temperature and amendment types that should be considered while recommending the use of biodigestate and biochar for formulating sustainable agricultural management practices to cultivate potatoes using combinations of organic and inorganic soil amendments.

Author Contributions: Conceptualization, A.A.F., F.A. and R.K.; methodology, A.A.F., F.A. and R.K.; software, F.A. and X.W.; validation, A.A.F.; formal analysis, R.K. and X.W.; investigation, A.A.F. and R.K.; resources, A.A.F.; data curation, R.K. and F.A.; writing—original draft preparation, R.K., F.A. and A.A.; writing—review and editing, A.A.F., A.A. and X.W.; Visualization, A.A.; supervision, A.A.F.; project administration, A.A.F.; funding acquisition, A.A.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Atlantic Canada Opportunities Agency. The authors are also thankful to the financial support from the Department of Environment, Energy and Climate Action, Government of Prince Edward Island through Climate Challenge Fund.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: Support from the following stakeholders and collaborators is appreciated: PEI Potato Board, PEI Provincial Department of Climate Change and Land, East Prince Environmental Association, Cavendish Farms, Agriculture Agri-Food Canada, Atlantic AgriTech Inc., and the precision agriculture group of the University of Prince Edward Island.

Conflicts of Interest: The authors declare no conflict of interest.

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