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SUMMARY OF DOCTORAL THESIS

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Title: Assessment of Pyrogenic Carbonaceous Soil Amendments on Greenhouse Gas Emissions in relation to Crop Productivity

(作物生産に関与する温室効果ガス排出における土壌改良材としての熱分解炭素質の評価)

Agricultural activities such as the use of chemical fertilizers, crop residue incorporation in soil, cultivation of leguminous crops which increase biological N fixation (BNF) have partly contributed to the significant increase in greenhouse gas (GHG) emissions especially nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4) that have resulted in global warming. One of the relatively cheaper technologies to achieve GHG mitigation in agriculture is the use of pyrogenic carbonaceous soil amendments such as biochar and activated carbon (AC) because they are not only available on farms after crop harvest, but also sequester carbon in soil, as well as improving crop productivity. The main objective of this study was to assess the effect of pyrogenic carbonaceous soil amendments on greenhouse gas emissions in relation to crop productivity. The specific objectives were to assess (i) the residual effects of palm shell biochar (PSB) on growth and yield of Komatsuna (*Brassica rapa* var. *perviridis*) under three continuous crop cycles without additional N fertilizer application after the first crop cycle; (ii) the impact of fresh and aged PSB on N_2O emissions, soil properties, nutrient content and yield of Komatsuna; (iii) the effect of crop residue and PSB incorporation on GHG emissions during the fallow and crop growing seasons of broccoli (*Brassica oleracea* var. *italica*); (iv) the effect of AC on GHG emissions, seed yield, soil chemical properties and isoflavone content of soybean genotypes with varying nodulation capacities; (v) the effect of AC on N_2O and CO_2 emissions from decomposing root nodules of the soybean genotypes.

In chapter two, a pot experiment was conducted to assess the residual effects of palm shell biochar (PSB) at 0, 6, 12, and 18% w/w of dry soil on growth and yield of Komatsuna. Biochar application in soils with fertilizer did not significantly influence crop yield and N uptake during the first crop cycle. However, with increased cultivation in these soils, biochar hindered N availability to plants and significantly reduced crop growth and yield during the third crop cycle. These results imply that the negative residual effects of PSB on crop growth and yield necessitate the need for more seasonal N fertilizer application in sandy soils which have been previously amended with biochar. It is necessary to assess the role of biochar in mitigating the negative effects (N_2O emissions and soil acidification) that accrue from the seasonal fertilizer application.

Chapter three focused on assessing whether the PSB applied in the previous experiment could still mitigate N_2O emissions even when additional basal N fertilizers are applied one year after the initial biochar application while comparing the effects with fresh PSB. The aged PSB non-significantly reduced N_2O emissions but significantly offset soil acidification, and maintained a high soil nutrient status. Biochar application with fertilizer significantly increased plant tissue K and Ca content but decreased N, P and Mg content compared to the treatments without biochar. At higher application rates, biochar had negative effects on crop yield but as it aged, the negative effects were offset as a result of the similar variation in plant N uptake. Since seasonal N fertilizer application seems to be inevitable in Komatsuna cultivation, addition of biochar could be a possible way of counteracting the effects of excessive fertilizer use.

In chapter four, a field experiment was conducted to evaluate the combined effect of broccoli crop residues and PSB incorporation on GHG emissions during the fallow (post-harvest) and crop growing seasons of broccoli. The treatments included; No-residues (NR), Residues (R), Residues + 10 t ha^{-1} PSB (R10), Residues + 20 t ha^{-1} PSB (R20) and Residues + 40 t ha^{-1} PSB (R40), arranged in a completely randomized block design. The results showed that the fallow season had significantly higher GHG emissions than the crop growing season. Incorporation of crop residues in soil significantly increased N_2O and CO_2 emissions but did not significantly affect CH_4 emissions when compared to those of the NR treatment. PSB amendment did not significantly affect N_2O, CO_2 and CH_4 emissions from crop residues and also the biomass and N uptake of the crop residues remaining after broccoli harvest. The application of PSB at 40 t ha^{-1} significantly increased the total N, total C, C/N ratio and exchangeable K but did not significantly affect soil pH, EC, available P, exchangeable Ca and Mg, and CEC. The large amounts of N_2O and CO_2 emissions emitted from broccoli crop residues during the fallow season may necessitate higher biochar application rates (>40 t ha^{-1}) to achieve the GHG mitigation potential of biochar while maintaining a high soil nutrient status.

Chapter five explains the effect of AC on GHG emissions, seed yield, soil chemical properties and isoflavone content of soybean genotypes with varying nodulation capacities under sandy soil conditions in a 2-year pot experiment. The soybean genotypes were TnVRSN4, Tachinagaha and TnVRNN4 with high, normal and low nodulation capacities respectively. AC was applied at rates equivalent to 0, 2.4, 4.8, and 9.6 t ha^{-1} in combination with inorganic fertilizers. AC tended to reduce soil N_2O emissions in the high nodulating genotype due to the significant reduction in nodulation but did not significantly affect CO_2 and CH_4 emissions. Highest CO_2 emissions and seed yield were observed in the high nodulating genotype and lowest in the low nodulating genotype. AC did not significantly affect seed yield of the high nodulating genotype but significantly reduced seed yield of the low and normal nodulation genotypes in 2017 and 2018 respectively. Although AC generally increased soil total N, total C and C/N ratio, its effect on soil pH, available P and exchangeable cations significantly varied with the soybean genotype. AC did not significantly affect root isoflavone, seed protein and total isoflavone content but significantly reduced the concentration of daidzein and daidzin which were exuded from soybean roots in soil. This implies that the effects of AC in soil under a particular soybean genotype may not have significant effects on the quality of the seeds. These findings suggest that the high nodulating genotype can perform better than other genotypes in marginalized sandy soils with a low nutrient status.

In chapter six, an incubation experiment was conducted to assess the effect of AC on N_2O and CO_2 emissions from decomposing root nodules of the soybean genotypes described above. The results showed that root nodules of the high and normal nodulating genotypes were important sources of N_2O and CO_2 emissions. These results clarified that the N_2O and CO_2 emissions from root nodules of the two genotypes applied in soil at the same amount did not significantly differ. AC did not have significant effects on cumulative N_2O and CO_2 emissions from the root nodules. To achieve sustainable soybean production, it could be possible to mitigate GHG emissions from the decomposing root nodules and increase soil nutrients by incorporating pyrogenic carbonaceous soil amendments after crop harvest.

The results from the above studies showed that pyrogenic carbonaceous soil amendments have a potential to significantly contribute to GHG mitigation while maintaining crop productivity in vegetable and soybean cropping systems. Compared to AC which could be expensive to most of the farmers, biochar could be an easily available and cheaper option to use by the farmers since it can be made at a local scale. There is need for long term studies on the different techniques of biochar production and usage (when to apply, how to apply and how much to apply) in soil while focusing on the changes in quality of the crop products obtained after biochar application to ensure safety for human consumption. Further research should also focus on exploring the aging effects of different biochars at varying application rates in different biochar types and crops before recommending it for use in the different soil types.