EVALUATING THE ROLE OF COMPOSTING SPENT COFFEE GROUNDS ON THEIR EFFICIENCY FOR SOIL AMENDMENT

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ABSTRACT

Using spent coffee grounds (SCG) as soil amendment could serve as a solution to two major issues by revalorising an abundant residue while reducing agriculture's dependence on harmful chemical fertilisers to feed a rapidly growing population. However, in light of the challenges SCG poses to soil quality and plant growth due to their acidity, phytotoxicity, and often high C:N ratio, this research aimed to assess how composting SCG before applying them could impact their efficiency for soil amendment. Caffeine content, pH, and soil respiration were measured, and a germination experiment was conducted with samples of SCG that had been composting for 0 to 4 weeks as well as with mixtures of composted SCG and soil at a rate of 1:10. The results found that composting SCG for only 4 weeks significantly increased pH and decreased the concentration of phytotoxic substances. Adding SCG to the soil at a rate of 1:10 increased soil respiration and had no significant impact on the germination of *Lepidium sativum* seeds, but composting also had no significant impact on the results when applied at this ratio. Overall, SCG has high potential to be applied for soil amendment and composting is a simple and efficient way to reduce their acidity, phytotoxicity, and prevent nitrogen immobilisation.

INTRODUCTION

Coffee is one of the most widely consumed beverages across the world (Cruz et al., 2012). It is especially highly consumed in developed countries, where coffee is integrated into the culture and lifestyle of many people (Torga and Spers, 2020). Coffee beans, primarily shipped in their green form, are the second most traded raw commodity after petroleum (Mussatto et al., 2011), with 10 billion kilograms produced in 2019-2020 (International Coffee Organisation, 2020). Furthermore, there is a growing demand for coffee globally; its production has increased by 60% since the 1990s (fig. 1) (International Coffee Organisation, 2020).

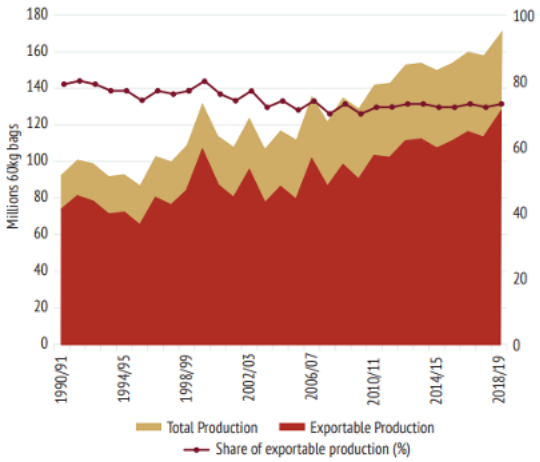

Figure 1: Coffee production and exports from 1990/91 to 2018/19 (International Coffee Organisation, 2020)

The coffee industry is responsible for significant pollution and waste production, from chemicals used in coffee farming, to transport, and wastage during the transformation process. Waste from the coffee industry includes spent coffee grounds (SCG), the leftover powder once coffee has been brewed (Mussato et al., 2011). This is a substantial source of waste in coffee-consuming countries: 2kg of wet SCG are generated for every kilogram of coffee brewed (Mussato et al., 2011). Processing and valorising waste is a key challenge for the coffee industry as landfills grow rapidly (Leow et al., 2021). When decomposing in landfills, SCG releases greenhouse gases and leaches caffeine into the environment, which is harmful to biodiversity (Murthy et al., 2012; Fernandes et al., 2017; Leow et al., 2021). With 6 million tons of SCG generated annually, it is essential to find ways to utilise and repurpose this residue (Cruz et al., 2012). Using this organic waste for soil amendment could fixate carbon in the soil and enrich the soil while also decreasing dependency on harmful chemical fertilisers in agriculture. Furthermore, as SCG is generated both on a large scale by the soluble coffee industry and on a smaller scale by households and local cafes, they have the potential to be applied both in large-scale agriculture and on a smaller scale in community or domestic gardens (Cruz et al., 2012).

SCG has potential in being used as organic fertiliser, since they are 35 times richer in organic carbon than soil (Cruz et al., 2015a). Increasing organic matter improves microbial activity, as well as nutrient and water availability for plants. Furthermore, as organic matter fixates carbon to the soil, one ton of SCG added to soil will prevent 506kg of CO_2 from being released into the atmosphere than if it had been discarded in landfill (Cervera-Mata et al., 2018). SCG is also rich in essential nutrients such as potassium, copper, iron, and nitrogen (Cervera-Mata et al., 2019). Moreover, the nutritional value of the crops grown in SCG-amended soil is higher than those grown with traditional fertilisers (Cruz et al., 2015b; Cervera-Mata et al., 2019).

Although using coffee grounds as soil amendment could be a more efficient way to process and repurpose this residue, there are certain challenges. For instance, SCG are acidic and contain chemicals such as caffeine, tannins, phenols, and chlorogenic acids, which can have toxic effects on soil microorganisms and plants (Cruz et al., 2012; Gomes et al., 2013; Hardgrove and Livesley, 2016). Hardgrove and Livesley (2016) conducted an experiment in which they observed that the addition of SCG to the soil significantly hindered growth in all plants studied. Similarly, Cruz et al. (2012) observed that adding SCG promoted growth of lettuce at amendment rates of 2.5-10%, but that at higher than 10% of soil volume growth was significantly hindered. Hardgrove and Livesley (2016) concluded that the reason SCG hindered plant growth was most likely due to phytotoxic effects from chemical compounds in the coffee grounds.

The majority of the available literature uses fresh SCG in their studies; therefore, it would be valuable to look at whether composting coffee grounds prior to application elsewhere could provide better results in terms of soil quality and plant

germination. The aim of this study is to evaluate the impact of composting SCG on its efficacy for soil amendment. This has been done by analysing the impact of composting on the pH and extractable organic substances of SCG as well as the impact on soil microbial activity and germination of *Lepidium sativum* (garden cress) when added to the soil at a rate of 1:10.

METHODS

Composting

Every week for four weeks, 2kgs of fresh SCG were collected from a local coffee shop and left to decompose in separate aerated static composting piles (Liu and Price, 2011). After four weeks, there were four heaps of SCG: one that had been decomposing for four weeks (C4); one for 3 weeks (C3); one for two weeks (C2); and one that had been left to decompose for one week (C1), as well as a fifth batch of fresh, undecomposed SCG collected on the same day (C0). Each heap contained 2kg of SCG, a relatively small amount that could be easily produced by a typical household's coffee consumption or obtained from a local coffee shop to apply in a garden.

Samples were collected from each stage of decomposition to be analysed in the lab, in order to assess the quality of the SCG by measuring its pH, caffeine content, and microbial activity, as well as undertaking a germination experiment. Furthermore, soil-coffee mixtures were also made in order to analyse how composted SCG will influence these parameters when mixed into soil at a ratio of 1:10. This aimed to assess whether adding SCG in a smaller quantity (1:10 ratio) would reduce its negative effects on soil quality. To create these mixtures, 300g of multipurpose compost and 30g of SCG were shaken to obtain a homogenous mixture. This was done with fresh coffee grounds (SC0) and with SCG that had been decomposing for one, two, three, and four weeks to obtain the mixtures named, respectively, SC1, SC2, SC3, and SC4. SCG and soil-coffee mixtures not analysed immediately were kept in the fridge.

pH

Soil pH is a measure of the H+ activity in the soil and is an important, easily measurable parameter of soil quality (Smith and Doran, 1997). The pH of each sample was measured by using a pH meter on three replicates of a solution that contained a slurry of either SCG, soil, or soil-coffee mixtures and deionised water at a ratio of 1:5.

Extractable organic substances

In order to measure the extent to which composting has broken down organic substances in the SCG, solutions containing 2.5g of sample with 10ml of deionised water were heated in a water bath at 52°C for 90 minutes and filtered. The filtrates were analysed through the Cecil CE 1011 Visible Spectrophotometer to measure their absorbance at a wavelength of 325nm. Although this method does not directly measure caffeine, it measures the presence of numerous other organic compounds present in coffee (including caffeine) and may be used as an indicator to observe changes in the concentration of these substances (Belay et al., 2008). Samples were diluted as necessary to obtain concentrations within the spectrophotometer's range. Filtrates not analysed immediately were kept in the fridge to be analysed the next day, as their absorption values are stable for at least 2 days (Alpdoğan et al., 2002).

Soil Respiration

Microbial activity in the soil is essential to break down organic matter and liberate nutrients to make them available for plants (Schloter et al., 2003). This was determined by measuring the amount of CO_2 released by the soil through respiration, according to the method described by Rowell (1995). For this, a red pH indicator solution that becomes more yellow as pH decreases was made with Cresol Red, as indicated by Rowell (1995).

A beaker with 30.0g multipurpose compost (S) was placed in an airtight jar along with a vial containing 15ml of Cresol red solution, as seen in plate 1. The same was done with the soil-coffee mixtures (SC0, SC1, SC2, SC3, and SC4), as well as a blank (B), with only the Cresol red solution and no soil. Four replicates of each treatment were made. Each jar was identical, kept in the same place at room temperature.

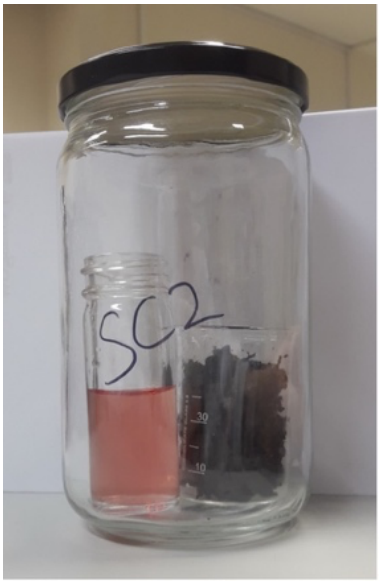

Plate. 1. Photograph of the experimental design of a jar used in the respiration experiment

After leaving the jars closed for 17 hours, the absorbance of the Cresol red solution at a wavelength of 572nm in each jar was recorded using the spectrophotometer (Rowell, 1995). The more yellow the solution, the lower the absorbance, indicating that the atmosphere in the jar was more acidic because more CO_2 was released by the soil (Rowell, 1995). The vials were refilled with Cresol red solution and the jars were resealed, a process repeated every 15-19 hours after sealing the jars, for four days – sufficient time for a difference to be observed, but not so long that the solutions would become saturated. The absorbance recorded was then converted to mg CO_2. h-1. kg soil-1 after calibration. Calibration standards were created by adding phosphoric acid to sodium bicarbonate to create a reaction that releases a known amount of gaseous CO_2. The jars were then left to sit overnight before measuring their absorbance at 572nm and plotting these results on a graph (fig. 2).

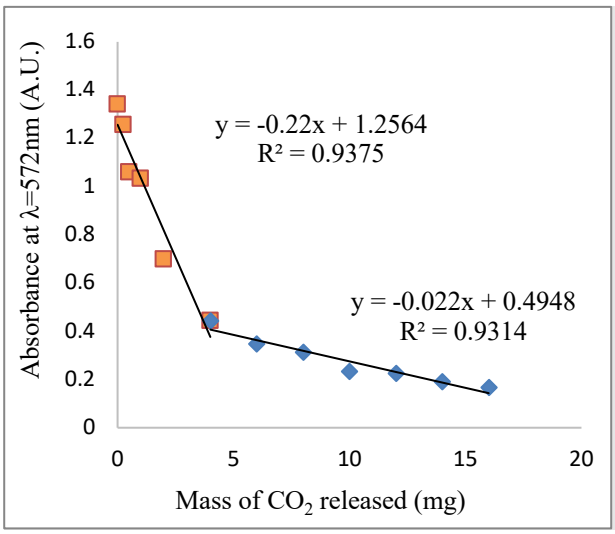

Figure 2: Calibration graph of the absorbance at λ=572nm by the mass of CO_2 released

The calibration points obtained did not have a linear relation and, since polynomial calibrations are less reliable, the points were divided into two separate linear functions, the equations of which were: (1) between 0mg and 4mg of CO_2 and for absorbance readings above 0.4; and (2) between 4mg and 6mg of CO_2 and for absorbance readings below 0.4:

(1) y=-0.22x+1.256

(2) y=-0.022x+0.495

In these equations, y is the absorbance at 572nm of the cresol red solutions and x is the mass of CO_2 released in the jar. Both calibration curves displayed good fitting to the linear functions (R^2=0.9375 and 0.9314). These equations were used to determine the mass of CO_2 released by the soil samples. The obtained result was then divided by the number of hours during which the jar had been sealed and the mass of soil in the jar (0.030kg), in order to obtain the rate of CO_2 released per hour per kg of soil (mg CO_2. h-1. kg soil-1).

Germination

A germination experiment was conducted to determine whether or not adding SCG at a 1:10 ratio had an impact on seed germination (Kapanen and Itävaara, 2001). Petri dishes were set out in a greenhouse, each containing 35g of soil or soil-coffee mixtures (S, SC0, SC1, SC2, SC3, and SC4), and 30 seeds of L. sativum. This was also done with C0 and C4. Five replicates of each treatment were made, each kept at the same temperature and sunlight exposure. They were watered equally with rainwater every 1-2 days. The number of germinated seeds in each petri dish was counted after 2 weeks and converted to percentages (Scott et al., 1984). An arcsine transformation of data was then performed before determining the significance of treatments' effects with an ANOVA test (Scott et al., 1984).

Statistics

Graphs were made using Excel; error bars were calculated using standard deviation. Statistical tests (Pearson's correlation; t-tests; regression) were performed using the Analysis Toolpak add-in on Excel. Analysis of Variance (ANOVA) and post-hoc statistical analysis (Tukey tests) was performed in R.

RESULTS AND DISCUSSIONS

pH

The pH measurements revealed that fresh coffee grounds are acidic, with a pH of 4.93. This is significantly lower than soil pH, which usually ranges from 6 to 7.5 in order to be suitable for most organisms (Smith and Doran, 1997). The multipurpose compost used in this experiment had a pH of 6.96. The acidic nature of fresh SCG can have negative impacts on plant growth when added to the soil, as low soil pH is linked to toxic levels of aluminium and manganese, and to low phosphorous availability (Kochian et al., 2004). In this experiment, when fresh SCG was added to the soil at a lesser rate of 10%, the soil's pH decreased to 6.15, which was a small yet significant decrease (t-test p-value=0.012), remaining within the suitable soil pH range presented by Smith and Doran (1997). According to Cruz et al. (2012; 2015a), acidity of SCG is especially problematic when applied at higher rates, such as 20% and above.

On the other hand, the acidity of SCG may also be used to reduce the pH of the soil deliberately to promote the growth of plants, such as blueberries or azaleas, which thrive in more acidic soils (Mickelbart et al., 2012). Likewise, fresh SCG may be used to reduce the pH of soils that are too alkaline (Morikawa and Saigusa, 2008). Alkaline soils have poor structure and low water infiltration capacity; their high pH decreases nutrient availability, which greatly hinders plant growth (Brautigan et al., 2014). Therefore, amending alkaline soils with SCG can be an organic and sustainable way to lower soil pH in order to improve conditions for plant growth (Morikawa and Saigusa, 2008). This would reduce the dependence on chemical fertilisers used traditionally to reduce soil pH, such as elemental sulphur, gypsum, or ammonium sulphate, which are expensive and have adverse impacts on the environment (Mickelbart et al., 2012; Brautigan et al., 2014).

Although the acidity of fresh SCG may be useful in certain situations, when dealing with neutral pH soils (as is the case in most gardens and agricultural fields), changing the pH of soil is not desirable as it disturbs the soil properties and negatively impacts plant growth (Smith and Doran, 1997; Kochian et al., 2004). However, in fig. 3, it can be observed that, during composting, pH increases both in the SCG and in the soil-coffee mixtures. In the SCG samples, pH increased from 4.93 when it was fresh to 6.46 after four weeks, an increase of 31%. A correlation test was performed on the set of replicates of the pH values of the coffee, which found a strong correlation (correlation coefficient = 0.968) between the pH of coffee and the number of weeks for which it had composted. The regression test (R^2 = 0.926) suggested a strong dependency between these two factors (p-value = 9.42x10-9 (<0.001)), highlighting that composting SCG is a simple and efficient way to increase its pH to be more neutral. Indeed, a significant increase in pH was already observable within the first week, and after only four weeks the pH of the SCG (C4) reached 6.46, almost as much as the control soil and within a suitable range for the majority of plants (Smith and Doran, 1997).

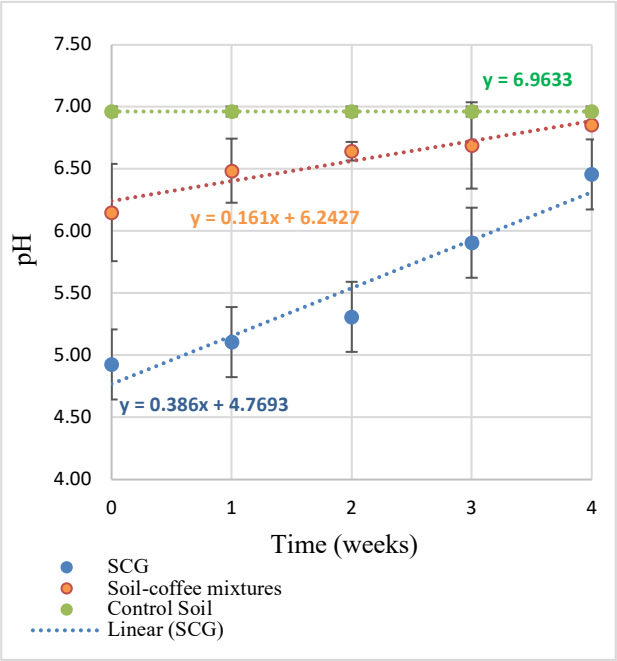

Figure 3: Graph of pH per time in weeks during which the coffee has been composting.

When fresh SCG was added to the soil at a 1:10 rate, the pH decreased from 6.96 in the control soil to 6.15 in SC0. The pH of the soil-coffee mixtures, however, increased as time of composting of the SCG increased (a strong positive correlation, as correlation coefficient = 0.957, and p-value < 0.05), until, when using 4-week-old SCG, the pH had increased to 6.85, much closer to the pH of the control soil. The regression test indicated a R^2 value of 0.523, suggesting an average dependency between the pH of soil-coffee mixtures and the time of composting (p-value = 0.002 (<0.05)). This concurs with the results of Liu and Price (2011) and Cruz et al. (2015b), who also recorded an increase in pH after composting SCG and soil-coffee mixtures (mainly during the first 4-6 weeks of composting). Similarly, Cervera-Mata et al. (2018) observed an increase in soil pH for the first two weeks of cultivation on soil amended with SCG, after which the pH stabilised. Overall, these results highlight that composting the SCG before adding it to the soil is a very simple, low-cost, and efficient way to avoid affecting the pH of the soil, and that significantly improved results may be obtained in only 4 weeks.

Extractable organic substances

The absorbance of fresh SCG at 325nm was almost 30 times higher than that of the control soil, indicating a strong concentration of organic compounds in SCG. This is very significant for soil amendment, as several of these components have phytotoxic effects on soil quality and plant growth (Hardgrove and Livesley, 2016). For instance, caffeine, a molecule naturally present in coffee plants as a chemical defence mechanism, causes early senescence in plants, inhibits germination, root and plant growth, and impairs protein metabolism (Batish et al., 2008; Kim and Sano, 2008; Mohanpuria and Yadav, 2009). Similarly, phenols, tannins, and chlorogenic acids present in SCG have toxic effects on plant growth (Gomes et al., 2013; Cervera-Mata et al., 2018). Indeed, Hardgrove and Livesley (2016) found that adding SCG significantly decreased the yield of five different horticultural crops studied, attributing this decrease to phytotoxicity. When added fresh, SCG has large amounts of these toxic molecules, which have negative impacts on plant growth; hence, decreasing the concentration of harmful compounds is essential to improve the efficiency of SCG as soil amendment (Cruz et al., 2012).

In fig. 4. it may be observed that, in the coffee samples, absorbance at 325nm decreases linearly as time of composting increases. Over the course of the four weeks of composting, the absorbance at 325nm of the coffee samples decreased by 91%. The correlation coefficient was -0.98, and R^2 value of linear regression test was 0.95, which suggests a strong correlation and dependency between absorbance and composting time (p-value = 4.68x10-10 <0.001). This is consistent with the results of Liu and Price (2011), Cruz et al. (2015b), and Cervera-Mata et al. (2020), who found that composting breaks down caffeine and phenols from SCG efficiently.

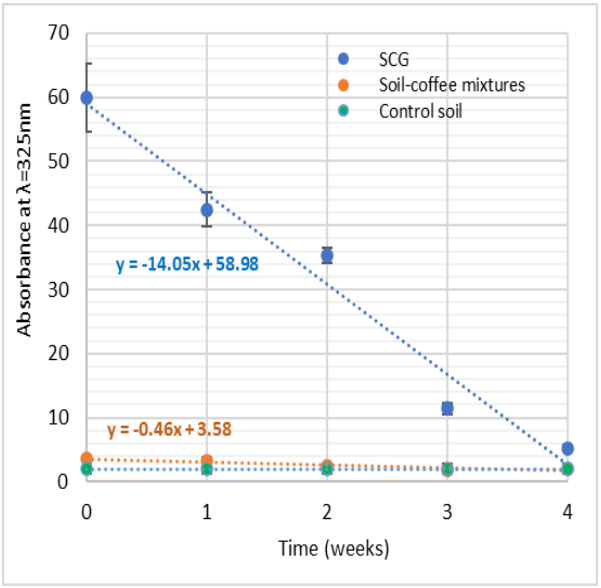

Figure 4: Graph of the absorbance at 325nm by the composting time (in weeks).

The control soil had an absorbance of 1.98 a.u. (arbitrary units) at 325nm. The soil-coffee mixtures with fresh SCG (SC0) had a significantly higher absorbance of 3.58 a.u. (p-value of t-test = 0.0195 <0.05). According to the Tukey test, however, when using 3- and 4-week-old SCG in the soil-coffee mixtures (SC3 and SC4) the absorbance was no longer significantly different to that of the control soil. The Pearson's test and linear regression tests revealed a negative correlation (correlation coefficient = -0.83) and a medium dependency (R^2 = 0.689) between the absorbance values of the soil-coffee mixtures and the time during which the coffee was left to decompose (p-value = 0.00014). This highlighted that composting decreased the concentration of organic compounds significantly, not only in coffee samples but also in soil-coffee mixtures.

With the soil-coffee mixture containing fresh SCG (SC0), absorbance levels were already 93.6% lower than in the pure fresh SCG (C0), and only 1.8 times more than the control soil. Hence, mixing soil with the SCG at a ratio of 10:1 appears to have a diluting effect on the concentration of extractable organic substances. Therefore, adding SCG at a smaller ratio, and composting it for a few weeks before application, are both efficient ways to reduce phytotoxicity.

Soil Respiration

The graph in fig. 5 illustrates that, overall, the treatments with SCG have higher rates of respiration than the control soil. The ANOVA tests confirmed that there was a significant difference between the treatments on the first and second day of measurements, as the p-values obtained were 3.97x10-5 and 1.03x10-5 (<0.001) respectively.

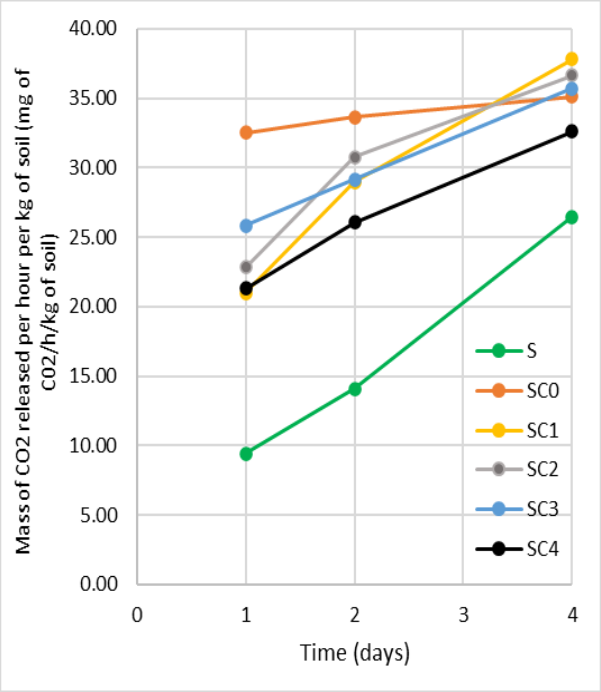

Figure 5: Rate of CO_2 release in the jar (in mg CO_2.h-1.kg soil-1) by day.

For further insight on the differences between the treatments on day 1, a Tukey test was performed. This revealed that, while there were no significant differences in respiration rate between the different soil-coffee mixtures (SC0, SC1, SC2, SC3, SC4), all were significantly higher than in the control soil. The Tukey test also revealed that the respiration in SC0 was significantly higher than in the SC4 and SC1 mixtures. Similar results were found on the second day, where there were no significant differences within the different composting times of SCG in the soil-coffee mixtures, but all were notably higher than the control soil. No measurements were taken on the third day due to limited lab access. On the fourth day, the ANOVA test revealed no significant differences in respiration between the different treatments (p-value = 0.114 >0.05).

The results of this experiment revealed that, when SCG is added to the soil at a ratio of 1:10, soil respiration increases significantly compared to the control soil. This concurs with the results of Cervera-Mata et al. (2018), who found that soil respiration rates were multiplied by 13 when SCG was added at a rate of 10%. This suggests that, at least when applied at this ratio, SCG does not seem to have any toxic impacts on soil microorganisms (Cervera-Mata et al., 2018). The increase in microbial activity may be explained by the fact that SCG is very rich in organic carbon (Cruz et al., 2015a), which is a source of energy for microorganisms (Reeves, 1997). Cervera-Mata et al. (2018) found that adding SCG stimulates soil microbial activity, as microorganisms such as fungal hyphae aggregate around coffee ground particles to degrade them. They also found that, as microorganisms degrade spent coffee ground particles, they improve and enrich the soil structure (Cervera-Mata et al., 2018).

Although this increase in microbial activity improves soil quality, it may also have negative effects on plant growth, as there is competition between the soil microorganisms and the plant roots for nitrogen (Cervera-Mata et al., 2020). When organic residues such as SCG are added to the soil, the first assimilation of inorganic nitrogen by soil microorganisms occurs (Chen et al., 2014; Hardgrove and Livesley, 2016). If there is insufficient nitrogen, all of it will be consumed by the soil microorganisms, resulting in nitrogen immobilisation: none of the nitrogen will be mineralised and made available to plants (Chen et al., 2014). This is often the case when the C:N ratio is high, such as in fresh SCG (Cruz et al., 2012; Cervera-Mata et al., 2018). Indeed, Cruz et al. (2012; 2015a), Hardgrove and Livesley (2016), and Cevera-Mata et al. (2019) all observed nitrogen immobilisation when SCG was added to the soil. Furthermore, the more SCG was added to the soil, the lower the nitrogen content in the plants (Cruz et al., 2012). Overall, nitrogen immobilisation increases with higher doses of SCG; therefore, it is important to apply it at smaller rates (Cruz et al., 2015a).

Despite this, nitrogen immobilisation does not always occur when SCG is added to the soil. For instance, Hardgrove and Livesley (2016) observed nitrogen immobilisation in loam soil, but the opposite (i.e., nitrogen mineralisation) was observed in sandy soils and sandy clay loam. This could be explained by the fact that Hardgrove and Livesley (2016) measured a lower C:N ratio in their SCG of only 23:1. Furthermore, they measured significant decreases in growth in all soil types and for all studied crops, even radish and viola, which have very low nitrogen requirements (Hardgrove and Livesley, 2016). Therefore, although nitrogen immobilisation may be one of the explanations behind the inhibition of plant growth, other factors such as phytotoxicity also play a role (Hardgrove and Livesley, 2016). Overall, whether the SCG will cause nitrogen immobilisation when added to the soil may depend on the SCG's initial properties, the rate at which it is applied, and the type of soil to which it is applied.

Composting SCG is an efficient way to reduce C:N ratio and prevent nitrogen immobilisation (Cervera-Mata et al., 2020). Around 30% of the total nitrogen in the SCG is in the caffeine molecules (Cruz et al., 2015a); composting SCG with soil, therefore, is an efficient way to break down caffeine in order for the nitrogen to become available to plants (Cruz et al., 2015b). Overall, composting the SCG could increase nitrogen availability to plants and prevent nitrogen immobilisation by decreasing C:N ratio due to the breakdown of caffeine molecules (Cruz et al., 2015a). It could also allow time for the microorganisms to complete the first assimilation of nitrogen before breaking down the rest of the organic matter and liberating nitrogen to make them available for plants through mineralisation (Schloter et al., 2003; Cervera-Mata et al., 2020).

By the fourth day of incubation, there were no longer significant differences between any of the treatments. This could be explained by the fact that the initial boost in microbial activity triggered by the addition of SCG had already started to reduce, and that more subtle differences between the treatments would require a more sensitive method.

Germination

Seeds germinated in all the treatments except the fresh SCG (C0), in which, after two weeks, no seeds had germinated in any of the replicates. On the other hand, in the petri dishes containing C4, an average of 62.7% of the seeds germinated. In fig. 6, the treatments with C4, SC0, SC1, SC2, SC3, and SC4 appear to have a higher percentage of germinated seeds than the control soil (S). However, when an ANOVA test was run on the data from all the treatments (except C0), after arcsine transformation (Scott et al., 1984), the p-value obtained was 0.09 (>0.05), which indicates that there are no significant differences between the treatments. However, they were all notably higher than C0.

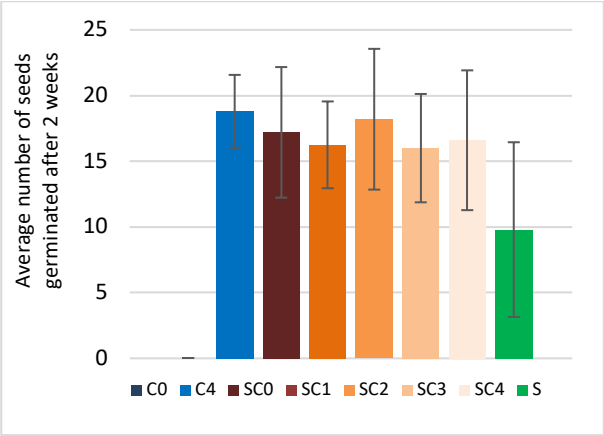

Figure 6: The percentage of seeds germinated after four weeks in each treatment.

The absence of seed germination in fresh SCG (C0) after four weeks may be explained by numerous SCG characteristics that hinder germination: low pH, high concentrations of toxic substances (caffeine, phenols, tannins, etc), and nitrogen immobilisation. However, in the petri dishes containing SCG that had been composting for 4 weeks, an average of 62.7% of the seeds germinated. This result indicates that composting time had a significant impact on improving the properties of the SCG to support germination. The previous experiments in this study indicated that composting SCG for four weeks significantly increased pH and significantly decreased the amounts of organic components present in coffee. These two results may explain why, after four weeks' composting, the SCG did not inhibit seed germination (Kochian et al., 2004; Mohanpuria and Yadav, 2009). Furthermore, as seen in the soil respiration experiment, there is evidence that composting could reduce or prevent N immobilisation caused by SCG (Cruz et al., 2015a).

When the SCG was added and mixed into the soil at a ratio of 1:10, there was no significant impact on the germination, even when using fresh SCG. This is an encouraging result, suggesting that the negative impacts of SCG on germination could be avoided as long as SCG is added at smaller rates. This is concurrent with the results of Cruz et al. (2012; 2015b), who found that adding fresh SCG at a rate of 10% or less had a positive impact on plant biomass, whereas adding SCG at a rate of more than 10% significantly inhibited plant growth.

Overall, results on the impact of SCG on germination are not constant across the available literature. Although some research, like the present study, has found that adding SCG at rates of 10% or less had positive impacts on plant growth (Cruz et al., 2012; 2015b), other studies observe significant inhibition in plant growth in all treatments with SCG, even when it was applied at rates of only 2.5% (Hardgrove and Livesley, 2016), or 5-15% (Cervera-Mata et al., 2019). This could be explained by the fact that the SCG used by different studies often has different initial properties, such as pH, C:N ratios, and caffeine contents. Therefore, further research should be conducted to study the impact of different varieties of coffee beans and the brewing methods on the properties of SCG and how this variety will affect soil quality and plant growth. The current study looked at applying SCG to the soil by itself, but it would be valuable to look at how mixing it with other organic residues such as manure and food waste could impact the overall efficiency and quality of the compost.

Moreover, Hardgrove and Livesley (2016) and Hirooka et al. (2021) found that, although SCG may be beneficial for weed control, it may also inhibit the germination of other plants. Hence, Hirooka et al. (2021) suggest that adding the SCG after germination is effective, as there is less growth inhibition of the crops but weed control is still efficient. Furthermore, long-term experiments have also found that most of the negative impacts of SCG reduce significantly or disappear with time (Kasongo et al., 2011; Yamane et al., 2014; Cruz et al., 2015b). This reinforces the proposal that composting the SCG before applying it could avoid its initial negative impacts (Cruz et al., 2015b).

It is important to treat the results of this germination experiment with caution, as the standard deviation values were high and only five replicates of each treatment were made. Indeed, germination experiments can potentially be inexact, as some seeds may be unviable to begin with and germination may be affected by a wide range of other factors (Scott et al., 1984). For more robust results, more replicates could have been made, with more seeds in each (Scott et al., 1984). Furthermore, measuring plant growth over a longer period of time would have been valuable to reveal impacts of the SCG in the longer-term (Kapanen and Itävaara, 2001), though this was not possible within the time frame of the present study. Despite this, the germination experiment conducted was sufficient to reveal that, at a 1:10 ratio, adding SCG to the soil had no significant negative impact on germination. The existing literature, however, presents varied results on how applying fresh SCG at different rates affects plant growth and germination. As such, further research needs to be conducted.

CONCLUSION

Overall, SCG may have both positive and negative impacts on soil quality and plant growth. On the one hand, it introduces nutrients and organic matter to the soil and increases the availability of nutrients for plants. On the other hand, its low pH and high concentration of toxic components (such as caffeine, phenols, chlorogenic acids, tannins), as well as the nitrogen immobilisation caused when it is applied to the soil, may all have negative impacts on plant growth.

The results of the experiments carried out in this study demonstrate that composting SCG before applying it to the soil is a simple and efficient method to mitigate negative impacts by increasing pH, decreasing concentrations of phytotoxic substances, and preventing nitrogen immobilisation by leaving time for the microorganisms in the soil to complete the first assimilation of nitrogen (after which nitrogen mineralisation occurs). Four weeks of composting was sufficient to improve these soil properties substantially. Furthermore, the rate at which the SCG is applied is an important factor to take into account, as higher rates will have more negative impacts on the soil. In this study, an SCG-to-soil ratio of 1:10 was used, which was sufficiently low to have no negative impacts on soil respiration or germination of L. sativum.

In conclusion, composting is a very efficient and accessible method to revalorise SCG, both on a large scale by soluble coffee industry and coffee shop chains for large-scale agriculture as well as, on a smaller scale, by individuals and small coffee shops. Composting SCG should be encouraged instead of disposal in landfill, as it can be beneficial to amend soils, especially when it is composted first. If soil is amended with fresh SCG, adding it at smaller rates (such as 1:10 as in this experiment), negative effects can be mitigated.

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