Agrochemical leaching reduction in biochar-amended tropical soils of Belize

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Abstract
The aim of this study was to determine the effects of biochar addition on agrochemical leaching in tropical soils of Belize. Biochars were produced from mixed softwood, rice husk and miscanthus straw, each pyrolysed at 700°C. Loam, sandy silt loam and clay loam tropical soils were amended with 0, 1, 2.5 and 5% (w/w) biochar to determine atrazine, diuron, enrofloxacine, oxytetracycline and tetracycline absorption in batch studies following OECD 106 guidelines. FOCUS groundwater modelling was performed with the results of the batch-sorption study and alterations to the soil profiles to explore the effect of biochar amendment on the leaching of atrazine in a risk assessment context. Results showed that agrochemical sorption was higher in biochar-amended soils than soils without biochar amendment. Soil organic matter content and biochar amendment contributed to the agrochemical sorption increase in soils. The FOCUS modelling showed a significant reduction in predicted environmental concentration in groundwater (PECgw) of atrazine when biochar was applied as a soil amendment. However, a trade-off was identified between the sorptive capacity of the biochar and the changes in hydrology in the soil as a result of the biochar incorporation. The amendment of Belizean tropical soils with rice husk biochar was shown to be an effective method to reduce the leaching of the selected agrochemicals, although widespread implementation should be conducted carefully, taking account of the potential trade-offs with biochar use identified in our modelling.

Highlights
- Biochar-amended soil is a feasible method to increase sorption and reduce agrochemical leaching to groundwater.
- Environmental fate modelling demonstrated that 1% and 2.5% biochar amendment could reduce atrazine leaching in soil.
- Modelling identified a biochar performance trade-off: altered soil hydrology could lead to greater leaching.
- Biochar implementation must account for trade-offs identified to ensure the mitigation works in each circumstance.
1 | INTRODUCTION

Agricultural production in Belize, as in many other developing tropical countries, continues to advance with the assistance of agrochemicals. However, if improperly managed, agrochemicals can leach through the soil and contaminate drinking, surface and groundwater (Fontecha-Cámara, López-Ramón, Álvarez-Merino, & Moreno-Castilla, 2007; Pan & Chu, 2017a). Therefore, the risk to non-target sites of agrochemical contamination is dependent on the physicochemical structure of the compound, properties of the soil, climatic conditions, land structure and agrochemical management practices (Bedmar, Gimenez, Costa, & Daniel, 2017; Liyanage, Watawala, Aravinna, Smith, & Kookana, 2006; Pan & Chu, 2017a). As such, many countries regulate the registration and use of chemicals in agriculture and these regulations require the applicant to demonstrate no unacceptable risk to the environment following the proposed use (e.g., Regulation 1107/2009 in the EU, FIFRA 7.8.136 in the USA). Tropical soils of Belize, in particular, are prone to agrochemical leaching due to improper soil management, such as excessive slash-and-burn practices (Chicas & Omine, 2015). Failing to mitigate agrochemical leaching in these soils could cause damaging effects on the tropical ecosystems of Belize (Wu, Rainwater, Platt, McMurry, & Anderson, 2000).

Despite concerns over the contamination of groundwater from the use of atrazine in agriculture (e.g., this led to the removal of atrazine from a re-registration process for use in agriculture in 2003 in the EU), it is still being widely used in Belize. Although diuron may be authorized for use in many countries worldwide, including Belize, it has also faced significant challenges in authorization in the past due in part to issues regarding groundwater and surface water contamination (Mrozik et al., 2019), following a lack of understanding regarding the degradation pathway of the active substance and its metabolites (e.g., the EU published a commission decision in 2007 deciding not to include diuron in Annex I of Directive 91/414/EEC; 2007/417/EC). Furthermore, veterinary antibiotic usage is increasing worldwide. In 2010, approximately 63,000 tons of veterinary antibiotics were used on livestock worldwide. Veterinary antibiotic use is predicted to increase to 106,600 tons in 2030 (Pan & Chu, 2017b). Enrofloxacine, oxytetracycline and tetracycline are antibiotics used in veterinary medicine that have been extensively used to prevent and control diseases whilst promoting growth in livestock. However, environmental contamination of veterinary antibiotics can be linked to intensive use. When veterinary antibiotics are metabolized by animals, approximately 90% of veterinary antibiotics are excreted with urine and 75% are excreted with faeces (Pan & Chu, 2017b). Usually, manure is applied to arable land. Consequently, these veterinary antibiotics can leach to surface and groundwaters (Carvalho & Santos, 2016).

Where there is a suggestion that concentrations in groundwater may exceed acceptable limits (e.g., 0.1 μg/L in the EU), risk mitigation may be implemented to continue the use of an agrochemical in an environmentally acceptable way. Improving soil structure, porosity and water holding capacity of tropical soils, through the use of soil amendments and land management, could improve soil aggregation and water retention, reducing leaching of contaminants (Dari et al., 2016).

One method to reduce agrochemical leaching is to amend tropical soils with biochar (Chaukura, Gwenzi, Tavengwa, & Manyuchi, 2016; Singh et al., 2014). Biochar is the production of carbonaceous material derived from the thermochemical conversion of biomass in an oxygen-limited environment (Beesley et al., 2011; Joseph et al., 2010). In addition to enhancing soil properties such as pH, bulk density, cation exchange capacity, soil hydrology, nutrient availability and organic carbon (Gamage, Mapa, Dharmakeerthi, & Biswas, 2016), biochar can be used to reduce agrochemical leaching due to its agrochemical-absorption effects (Kookana, 2010; Trinh, Werner, & Reid, 2017; Yang, Sheng, & Huang, 2006; Zhelezova, Cederlund, & Stenström, 2017). Cederlund, Börjesson, and Stenström (2017) studied the effects of wood-based biochar produced at 380–430°C on reducing the leaching of chlorpyrifos, diuron, glyphosate and MCPA, recommending that biochar be used as a pesticide-absorptive layer over the soil surface. Meanwhile, cassava waste biochar produced at 750°C was used to reduce the transport of atrazine in agricultural soils, showing a negative correlation with decreasing mobility of the pesticide with the addition of biochar (Deng et al., 2017), whereas Manna, Singh, and Singh (2018) reported in an in-vitro study that biochar application to soil had only a marginal effect on pyrazosulfuron-ethyl leaching.

Therefore, there is evidence that in some circumstances biochar has the potential to increase sorption of agrichemicals and reduce leaching to groundwater. Taking this hypothesis further, modelling has been suggested as a suitable approach to identify the full implications of biochar for agrochemical sorption in the soil (Queyrel,
Habets, Blanchoud, Ripoche, & Launay, 2016) in a “real-world” scenario. A limitation of these previous studies is that they have looked at sorption of biochars in isolation, whereas multiple chemicals may be present at a given time in a given field and so the performance of biochar should be assessed in these multi-chemical complexes to explore the potential limitations of their leaching-reducing potential, through batch sorption studies with mixtures.

Although many studies have focused on the effects of biochar on pesticide leaching, only a handful of studies have focused on antibiotic absorption (Ahmed et al., 2017; Huang et al., 2017; Yao et al., 2013). To our knowledge, no studies have focused explicitly on the absorption of enrofloxacine, oxytetracycline and tetracycline in the presence of biochar. Thus, we have performed batch-sorption studies with these substances to fill this gap in the literature and consider the need for biochar to prevent leaching issues following their widespread use. We explored the hypothesis that the soil physicochemical changes caused by biochar amendment, along with the method of biochar amendment and the biochar characteristics such as high surface area and ash content, should reduce agrochemical leaching in tropical soils. In addition, although in a biochar-amended soil agrochemical sorption is dominated by the presence of biochar, high organic matter and clay contents of the soil are also expected to help in reducing agrochemical leaching, but to what extent? Furthermore, the physicochemical structure of the agrochemical has an important role in its ability to leach down a soil profile; for example, some antibiotics have strong intermolecular attraction and are able to penetrate into absorbent layers, and thus have a higher sorption coefficient.

Therefore, the aim of this study was to determine the effects of biochar addition to agrochemical leaching in various tropical soils from Belize, by (a) performing batch-sorption studies with different biochars to explore their performance in sorption of different chemicals present in a mixture and (b) exploring the real-world implications of pesticide sorption with regards to risk assessments and the potential of biochar to mitigate leaching risk associated with some widely used, yet contentious, pesticides.

2 MATERIALS AND METHODS

2.1 Soil

Soil samples were collected from three locations in Belize using soil cores. These locations varied in soil texture and land management. The soils were collected from the A horizon of the soil profile, at a depth of 0–20 cm. The clay loam soil was collected from a sugarcane plantation in Corozal District, Northern Belize (18°13′44.6″ N, 88°32′07.3″ W). The loam soil was collected from an agricultural land in Cayo District, Western Belize (17°12′04.4″ N, 89°00′16.6″ W), that practised crop rotation of maize and beans. The sandy silt loam soil was collected from a citrus orchard in Stann Creek District, Southern Belize (16°59′40.9″ N, 88°21′49.0″ W). The land has been cultivated with citrus crops for over 30 years. These soil-sampling sites represent the dominant soil types being used for agriculture in Belize. Samples were air-dried and sieved through a 2-mm sieve and carefully homogenized. Soil properties were analysed by Lancrop Laboratories, New York, UK. Soil pH, cation exchange capacity (CEC), organic matter (OM) and organic carbon (OC) were analysed following the method described by Obia, Cornelissen, Mulder, and Dörsch (2015). Table 1 shows the characteristics of each soil type.

2.2 Biochar

The experiments used three types of well-characterized biochars produced under standardized conditions and provided by the UK Biochar Research Centre (UKBRC) at the University of Edinburgh (www.biochar.ac.uk). These biochars were selected due to their feedstock availability in tropical regions and potential to absorb agrochemicals (Carter, Shackley, Sohi, Suy, & Haefele, 2013; Vithanage, Mayakaduwa, Herath, Ok, & Mohan, 2016). They were produced from feedstock of softwood pellets, rice husk and miscanthus straw pellets in a stage III pilot-scale pyrolysis unit at 700°C. As provided by the UKBRC, the physicochemical characteristics of the different biochar types are given in Table 2.

2.3 Chemicals, reagents and materials

The two herbicides used in this experiment were analytical grade atrazine (1-Chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine) of 98.9% purity and diuron (1,1-dimethyl, 3-(3′,4′-dichlorophenyl) urea) of 98% purity, both purchased from Sigma-Aldrich Ltd, Havergate, UK. These herbicides are used to prevent pre- and post-emergence broadleaf weeds in crops such as maize and wheat. The antibiotics used in this experiment were enrofloxacine (1-Cyclopropyl-7-(4-ethyl-1-piperazinyl)-6-fluoro-4-oxo-1,4-dihydro-3-quinolinecarboxylic acid) of high performance liquid chromatography (HPLC) grade 98% purity, oxytetracycline hydrochloride (4S,4αR,5S,5αR,6S,12αS)-(4-(dimethylamino)-1,4,4α,5,5α,6,11,12α-octahydro-3,5,6,10,12α-hexahydroxy-6-methyl-1,11-dioxo-2-naphthacenecarboxamide hydrochloride) of HPLC grade 95% purity, and tetracycline hydrochloride (6-methyl-1,11-dioxy-2-naphthacenecarboxamide) of 98% purity.
purity. Enrofloxacine and oxytetracycline hydrochloride were purchased from Sigma-Aldrich Ltd and tetracycline hydrochloride was purchased from Fluka Analytical, Gillingham, UK.

2.4 Batch sorption experiments

Sorption was measured in a batch equilibrium system according to the indirect method in OECD 106 guidelines for testing of chemical absorption using the batch equilibrium method (OECD, 2000). The experimental design consisted of four factors: soil type, biochar type, biochar rate and agrochemical type, with three replicates. The first step of the experiment consisted of agrochemical sorption to biochar only. Three replicates each of softwood, rice husk and miscanthus straw biochar types were sieved to <2 mm and separately weighed at 50, 100, 150, 200, 250, 300, 350, 400, 450 and 500 mg. Each weighed biochar was then placed in a 60-mL amber glass

| Analysis                      | Corozal district | Cayo district | Stann Creek district |
|-------------------------------|------------------|---------------|---------------------|
| FAO soil classification       | Vertic gleysol   | Gleyic cambisol | Gleyic acrisol     |
| Soil class                    | Clay loam        | Loam          | Sandy silt loam    |
| pH                            | 8.2              | 8.1           | 6.1                |
| CEC (meq/100 g)               | 69.9             | 27.5          | 11.4               |
| Organic matter (%)            | 5.0              | 2.9           | 3.7                |
| Organic carbon (%)            | 2.91             | 1.68          | 2.15               |
| Silt (%)                      | 37.66            | 41.37         | 48.02              |
| Clay (%)                      | 34.93            | 20.54         | 15.83              |
| Sand (%)                      | 27.41            | 38.09         | 36.15              |
| Iron (ppm)                    | 54               | 174           | 506                |

**TABLE 2** Material properties of three biochar types

| Property                      | Unit       | Mixed softwood pellets | Rice husk | Miscanthus straw pellets |
|-------------------------------|------------|------------------------|-----------|-------------------------|
| Pyrolysis temperature        | °C         | 700                    | 700       | 700                     |
| Dry matter                   | g/kg       | 990                    | 985       | 988                     |
| Biochar yield                | Wt % (d.b.)| 17.34                  | 32.77     | 21.07                   |
| Moisture                     | Wt % (a.r.)| 1.00                   | 1.49      | 2.23                    |
| Total ash                    | Wt % (d.b.)| 1.89                   | 47.93     | 11.55                   |
| pH                            |            | 8.44                   | 9.81      | 9.72                    |
| C_{tot}                      | Wt % (d.b.)| 90.21                  | 47.32     | 79.18                   |
| O:C_{tot}                    | Molar ratio| 0.05                   | 0.03      | 0.07                    |
| H:C_{tot}                    | Molar ratio| 0.24                   | 0.16      | 0.19                    |
| H                             | Wt % (d.b.)| 1.83                   | 0.63      | 1.26                    |
| O                             | Wt % (d.b.)| 6.02                   | 2.06      | 6.99                    |
| Total N                      | Wt % (d.b.)| <0.1                   | 0.85      | 1.03                    |
| Mineral N                    | Mg/kg (d.b.)| <3                     | <3       | <3                      |
| Total P                      | Wt % (d.b.)| 0.07                   | 0.16      | 0.76                    |
| Total K                      | Wt % (d.b.)| 0.28                   | 0.62      | 2.60                    |
| Total surface area           | m²/g       | 162.3                  | 42        | 37.2                    |
| Volatile matter              | Wt % (d.b.)| 6.66                   | 4.99      | 7.71                    |
| Electric conductivity        | μS/cm      | 160                    | 690       | 1910                    |
| Biochar C stability          | % C-basis  | 97.27                  | 100.18    | 98.93                   |

**Note:** d.b., dry basis; a.r., as received. Further data can be found at the UK Biochar Research Centre.
vial. To prepare the stock solution, 10 mg of tetracycline, oxytetracycline and diuron were separately measured and separately solubilized with 10 mL of methanol; 10 mg of atrazine was solubilized with 10 mL of acetonitrile. Methanol measured at 5 mL combined with 5 mL of acetonitrile was used to solubilize 10 mg of enrofloxacin. The stock solutions were stored in amber glass vials and kept closed in the dark at 4°C. The working solution was prepared with 1 mL of the stock solution per agrochemical and mixed in 1 L of HPLC grade water in a 1-L amber glass vial; 50 mL of this mixture was then poured into the amber glass vial, which contained the previously weighed biochars. These were then shaken at 200 rev min⁻¹ for 24 hr at room temperature of 20 ± 2°C.

The second step of the experiment consisted of agrochemical sorption to soil only. Three replicates of each soil type separately weighed to 500, 1,000, 2,000, 5,000 and 10,000 mg were prepared according to OECD 106 guidelines (OECD, 2000).

The third step consisted of amending the soils with one selected biochar that best absorbed the agrochemicals. Soils were then amended with biochar at rates of 1%, 2.5% and 5% (w/w) per 10,000 mg of soil. Except for changes in absorbent matrix, all other procedures were the same throughout the experiment. In all cases, separate controls consisted of amber glass vials containing 0.01 M CaCl₂ solution only, 0.01 M CaCl₂ solution and biochar only, 0.01 M CaCl₂ solution and soil only and 0.01 M CaCl₂ solution with agrochemical only. Each control was in triplicate. The aqueous solutions were analysed using high-performance liquid chromatography. The lower limit of detection ranged between 1 and 10 μg/L (at least two orders of magnitude below the nominal working solution concentration of 1 mg/L) for the agrochemicals investigated. No significant adsorption of any of the agrochemicals onto the glass vials occurred.

2.5 | Statistical analysis

Statistical analysis was conducted on sorption data using IBM SPSS Statistics 24. The difference between the measured aqueous concentration in the batch with the absorbent and the control batch without the absorbent was statistically determined. The data were evaluated for normality (Shapiro–Wilk test), then using a paired sample t-test (p < .05). In addition, the difference between the measured aqueous concentration and zero was statistically determined by calculating the standard error of the mean. When the mean was at least twice as much as the standard error, then the measured aqueous concentration was qualified as statistically significantly different to zero. Measurements showing an apparent increase in aqueous concentration above the control batches without sorbents were excluded. For isotherm fitting, a minimum five data points and minimum factor five difference between the lowest and highest measured aqueous concentration was mandated. Only the datasets that met all criteria were used to plot sorption isotherms (see Tables S2–S4). Sorption data were fitted to linear, Langmuir or Freundlich isotherms using minimization of least squares residuals between isotherm predictions and data. The fittings were optimized using the fminsearch function of Matlab R2017a.

2.6 | Environmental fate modelling

Based on the results from the batch-sorption studies, environmental fate modelling was performed with atrazine in both control and biochar-amended soil simulations in order to explore the potential of biochar to mitigate leaching of atrazine in a regulatory context.

2.7 | Control simulations

An initial set of groundwater modelling in FOCUS PEARL v.4.4.4 was performed using the standard scenario definition for Sevilla from FOCUS (2000, 2014) with the agreed substance endpoints for atrazine from Lewis, Tzilivakis, Warner, and Green (2016) and a representative application scheme (Hamill & Zhang, 1997). Specifically, the application scheme was a single application of 1,130 g a.s./ha on maize at 14 days before emergence (0% crop interception). This provided the control predicted environmental concentration in groundwater (PECgw), defined as the predicted concentration at 1 m depth for the 80th percentile from a 20-year simulation.

2.8 | Experimental simulations

Soil may be amended with biochar in different ways (i.e., added as a surface layer of different depths or incorporated at different amounts to different depths). To explore how the latter of these potential uses could alter the leaching of atrazine to groundwater, the control scenario from FOCUS PEARL v.4.4.4 was altered to reflect the amendment of the soil with either 1 or 2.5% biochar to either 5 or 10-cm soil depth. The sorption of atrazine was altered in the substance properties to reflect the results of the batch-sorption study. The geometric mean Kf from all four biochar-amended soils (with rice husk biochar) was implemented in the model using the option Kf user-defined (Kf of 4.5 mL/g for 2.5% biochar-amended soil and 3.83 mL/g for 1% biochar-amended soil). The soil
horizons were altered to reflect both the composition of biochar and the change in hydraulic properties of the soil. The topsoil horizon in each scenario was altered to include either a 5 or 10-cm horizon of biochar-amended soil. The factor for the effect of depth on sorption (FacZSor) was inputted to the soil profiles, with a value of 1 used in the soil horizon amended with biochar and the value used in all other soil horizons calculated as the default KF (3.2 mL/g) divided by the KF from the relevant batch-sorption study. The characteristics of the biochar-amended soil horizon were changed to reflect soil amended with either 1% or 2.5% biochar. Specifically, the soil organic matter and the bulk density (Rho) were altered from the original scenario. For example, horizon 1 in the control simulation for Sevilla had an organic matter of 0.016 (1.6%), whereas that used in the 2.5% biochar-amended soil horizon had an organic matter of 0.022 (2.2%), which accounts proportionally for 2.5% of organic matter of the biochar (at 27.4%) and 97.5% of the control soil (at 1.6%). The hydraulic properties of the soil were also altered (as they are associated with a change in bulk density) using the standard USDA Texture Class and Rosetta function. This provided PECgws that were compared with that from the control simulation to explore the influence of biochar on the leaching of atrazine to groundwater. The main details of the application schemes and substance properties are provided in Table S1 for the Sevilla scenario.

3 | RESULTS

3.1 | Soil sorption experiments

The sorptive behaviour of each agrochemical differed in every soil type. Based on the Kd coefficients, the soil sorption of antibiotics was much higher than that of the herbicides (see Table 3). All of the studied antibiotics were detected in the aqueous phase of the loam soil, with tetracycline having the highest absorption coefficient, followed by oxytetracycline and enrofloxacine. Furthermore, enrofloxacine and oxytetracycline were only

| Sorbate       | Sorbent               | Biochar amendment (%) (w/w) | Kd ± SD (L/kg) | KBC ± SD (L/kg) |
|---------------|-----------------------|-----------------------------|----------------|-----------------|
| Oxytetracycline| Clay loam             | -                           | 434 ± 95       | -               |
|               | Loam                  | -                           | 484 ± 30       | -               |
| Tetracycline  | Loam                  | -                           | 1,040 ± 31     | -               |
|               | Sandy silt loam       | -                           | 971 ± 26       | -               |
| Enrofloxacine| Clay loam             | -                           | 216            | -               |
|               | Loam                  | -                           | 123 ± 121      | -               |
| Atrazine      | Clay loam             | -                           | 2 ± 0          | -               |
|               | Clay loam + RHB       | 1                           | 9 ± 0          | 850 ± 24        |
|               | Clay loam + RHB       | 2.5                         | 25 ± 1         | 991 ± 47        |
|               | Clay loam + RHB       | 5                           | 95 ± 16        | 1896 ± 320      |
|               | Loam + RHB            | 1                           | 13 ± 1         | 1,286 ± 143     |
|               | Loam + RHB            | 2.5                         | 125 ± 4        | 4,986 ± 541     |
|               | Sandy silt loam + RHB | 1                           | 8 ± 1          | 790 ± 129       |
|               | Sandy silt loam + RHB | 2.5                         | 41 ± 5         | 1,621 ± 186     |
|               | Sandy silt loam + RHB | 5                           | 239 ± 22       | 4,775 ± 436     |
| Diuron        | Clay loam             | -                           | 0 ± 0          | -               |
|               | Clay loam + RHB       | 1                           | 141 ± 21       | 14,084 ± 2067   |
|               | Loam                  | -                           | 0 ± 0          | -               |
|               | Loam + RHB            | 1                           | 176 ± 41       | 17,635 ± 4,067  |
|               | Sandy silt loam       | -                           | 3 ± 1          | -               |
|               | Sandy silt loam + RHB | 1                           | 86 ± 23        | 8,592 ± 2,338   |

Note: KBC is the inferred biochar adsorption coefficient in the amended soil matrix, which was calculated by assuming that the biochar was the main herbicide sorbent in the amended soils.

Note: RHB, rice husk biochar; SD, standard deviation.
detected in the aqueous phase of the clay loam soil, with oxytetracycline having a higher $K_d$ (434 L/kg) than enrofloxacaine (216 L/kg). Tetracycline was the only antibiotic that could be detected in the aqueous phase of the sandy silt loam soil (see Table 3). Non-detection of any of the agrochemicals in the aqueous phase of a soil could be due to method limitations in the batch experiments, whereby the soil to water ratio was inadequate. However, non-detection of these agrochemicals indicates strong sorption by the soil. The focus of this study was on the compounds only weakly bound by the soil matrix, to investigate how biochar amendment may enhance the compound retention.

As for the herbicides, diuron was only absorbed by sandy silt loam soil with a low $K_d$ of 3 L/kg. The sorption of diuron by sandy silt loam soil indicated that diuron had a lower potential to move from the solid to the aqueous phase of this soil type as compared to the others (Inoue et al., 2004). Atrazine was only sorbed by the clay loam soil with a low $K_d$ of 2 L/kg. Similar to diuron, atrazine sorption was highest in the clay loam soil. The sorption coefficients for atrazine in loam and sandy silt loam soils were not reported because its concentrations in the aqueous phase of the soils did not significantly differ from the control ($p < .05$) (see Table S2). These statistical results showed that the loam and sandy silt loam soils were not able to significantly absorb atrazine, thus indicating that these soils could be prone to atrazine leaching.

### 3.2 | Biochar sorption

Based on the absorption coefficients ($K_d$) for the different agrochemicals sorbed, the rice husk biochar had the highest $K_d$ for all of the studied agrochemicals as compared to softwood and miscanthus straw biochar (see Table 4). Rice husk biochar was also the only biochar for which sorption data covering a wide enough aqueous concentration range to meaningfully fit isotherms could be obtained. The rice husk biochar sorption data generally best fitted the Freundlich isotherm model (see Figure 1). These results demonstrated that rice husk biochar was the best sorbent for the agrochemicals, as compared to softwood and miscanthus biochars. Rice husk biochar had the highest ash content of 47.9% (wt %), as compared to mixed softwood and miscanthus, which had 1.9 and 11.6% (wt %), respectively. In addition, the rice husk biochar molar H/C and O/C ratios were less than the softwood and miscanthus biochars, indicating greater carbonization (see Table 2).

### Table 4  Absorption coefficients ($K_d$) for different compound and biochar types and sorption isotherm fitting for rice husk biochar

| Agrochemical | Biochar | $K_d$ (L/kg) | SD | $C_{max}$ (mg/kg) | $K_l$ (L/mg) | SSR (mg/kg)$^2$ | $R^2$ | $K_f$ | 1/n | SSR (mg/kg)$^2$ | $R^2$ |
|--------------|---------|-------------|----|------------------|-------------|----------------|------|------|-----|----------------|------|
| OXY          | RH      | 4,069       | 1,572 | 7.1E+02         | 8.9         | 1.8E+04        | 1.0  | 887.0 | 0.5 | 1.6E+04       | 1.0  |
|              | SW      | 123         | 71   | -                | -           | -              | -    | -    | -   | -              | -    |
|              | MS      | 171         | 34   | -                | -           | -              | -    | -    | -   | -              | -    |
| TETRA        | RH      | 7,362       | 2,326 | 1.7E+03         | 5.3         | 4.3E+04        | 0.9  | 2,775.7 | 0.7 | 3.4E+04       | 1.0  |
|              | SW      | 136         | 77   | -                | -           | -              | -    | -    | -   | -              | -    |
|              | MS      | 1,459       | 2,038 | -                | -           | -              | -    | -    | -   | -              | -    |
| ENRO         | RH      | 2,092       | 1,286 | 2.6E+02         | 21.4        | 8.2E+03        | 0.9  | 316.1 | 0.3 | 5.9E+03       | 0.9  |
|              | SW      | 666         | 664  | -                | -           | -              | -    | -    | -   | -              | -    |
|              | MS      | 121         | 14   | -                | -           | -              | -    | -    | -   | -              | -    |
| ATR          | RH      | 1,068       | 668  | 2.1E+02         | 16.4        | 5.6E+03        | 0.8  | 236.2 | 0.3 | 2.5E+03       | 0.9  |
|              | SW      | 36          | 6    | -                | -           | -              | -    | -    | -   | -              | -    |
|              | MS      | 26          | 5    | -                | -           | -              | -    | -    | -   | -              | -    |
| DIUR         | RH      | 10,397      | 8,713 | 4.3E+02         | 33.4        | 6.0E+04        | 0.9  | 581.5 | 0.3 | 8.5E+03       | 1.0  |
|              | SW      | 108         | 26   | -                | -           | -              | -    | -    | -   | -              | -    |
|              | MS      | 87          | 12   | -                | -           | -              | -    | -    | -   | -              | -    |

**Abbreviations**: ATR, atrazine; DIUR, diuron; ENRO, enrofloxacine; MS, miscanthus straw biochar; OXY, oxytetracycline; RH, rice husk biochar; SD, standard deviation; SSR, sum of squared residuals between measured and predicted solid phase concentrations; SW, softwood biochar; TETRA, tetracycline.
3.3 | Biochar-amended soil sorption

The biochar sorption experiments showed that rice husk biochar was the best sorbent for the agrochemicals used in this study. Therefore, rice husk biochar was used as a soil amendment for these sorption experiments. The antibiotics were all non-detectable in the aqueous phase of all three biochar-amended soils. The antibiotics were non-detectable even at a low biochar amendment of 1% (w/w), indicating minimal concentration, and hence mobility in the aqueous phase. On the other hand, diuron was detectable in soils amended with 1% (w/w) biochar but was non-detectable in all of the soils amended with 2.5 and 5% (w/w) biochar. However, atrazine was detectable in the aqueous phase of the clay loam and sandy silt loam even when the soil was amended with 5% (w/w) rice husk biochar. However, atrazine was non-detectable in the aqueous phase of the loam soils with 2.5% (w/w) biochar amendment. In addition, as biochar dosage increased, the absorption coefficient of the herbicides increased for both the biochar-amended soil matrix and the inferred sorption coefficient of the rice husk biochar in the soil matrix (see Table 3). This indicates reduced biochar fouling by soil organic matter at higher biochar dosage, which facilitates herbicide sorption and/or non-linearity of the sorption isotherm (see Figure 1). Overall, herbicide sorption was much higher in a biochar-amended soil, even at a minimum biochar amendment of 1% (w/w), as compared to soils without biochar amendment.

3.4 | Environmental fate modelling

The PECgw for the Sevilla control simulation was 3.405 μg/L. The PECgw in all cases where the soil had been amended with biochar was lower than that in the control scenario. The PECgw in Sevilla using biochar was approximately four to five times lower than in the control simulations without biochar, as seen in Figure 2. The largest reductions in the PECgw were observed in the scenarios with 10 cm of biochar-amended soil, although the largest drops in PECgw were between no biochar and some biochar, rather than between 5 cm of biochar and 10 cm of biochar (i.e., some is much better than none, but more is only slightly better than some). In addition, 1% amendment with biochar actually resulted in a greater reduction in PECgw than 2.5% biochar, indicating that the sorptive capacity of the biochar was not the only reason for the reduction in PECgw and the changes in bulk density and associated hydrology play an important role in the predictions. No simulations resulted in a PECgw below the Tier 1 threshold in the EU of 0.1 μg/L; however, results with biochar were below the higher thresholds associated with non-relevant metabolites (either 0.75 or 10 μg/L) and other standard mitigations that would reduce the PECgw further were not explored.
(e.g., crop growth stage and interception, application timing, biennial applications, etc.).

4 | DISCUSSION

4.1 | Soil sorption experiments

According to Site (2000), antibiotics are strongly sorbed to soil due to the soil’s monofunctional nature and the antibiotic’s strong intermolecular attraction and ability to penetrate into absorbent layers. Tolls (2001) has also stated that the sorption of antibiotics is a surface-related process. Sorption tends to occur very fast (Sengeløv et al., 2003). Notably, the antibiotics will have sorbed strongly to the soil organic matter and clay particles (Samuelsen, Torsvik, & Ervik, 1992; Tolls, 2001). The strong sorption of these antibiotics suggests that their ability to leach to groundwater is low (Liu, Song, Zhao, & Wang, 2020). However, their strong sorption does not mean that they become entirely inactive in the soil. Without any intervention to reduce their bioaccessibility, these antibiotics can remain active in the soil and influence the presence of antibiotic-resistant bacteria (Kemper, 2008). Active antibiotics in the soil are capable of reducing soil microbial populations (Kim, Fan, Prasher, Patel, & Hussain, 2011). Therefore, if antibiotics and herbicides are both present in a soil matrix without any soil amendment intervention, herbicide degradation could be hindered if soil microbial populations that are responsible for herbicide degradation are reduced. Although not definitive, the low aqueous concentrations (or non-detects) of antibiotics in our study does support the literature position that sorption of enrofloxacine, oxytetracycline and tetracycline in soil is high. The need for biochar to ameliate leaching of these antibiotics to groundwater is therefore limited and future research would be better focussed on determining the activity of these substances whilst in the soil and their interaction with other substances present.

As for herbicides, their sorption to the soil is also influenced by organic matter and clay content (Kookana, Baskaran, & Naidu, 1998; Naidu & Kim, 2008; Worrall, Parker, Rae, & Johnson, 1997). As seen in Table 1, the clay loam soil contained the highest organic matter and clay content as compared to the loam and sandy silt loam soils. Therefore, the high organic matter and clay content explained why the herbicides had a higher sorption to clay loam than the other soils. Notably, there is a positive correlation between herbicide absorption and organic matter and clay content (Baskaran, 1994; Bedmar et al., 2017; Nemeth-Konda, Füleky, Morovjan, & Csokan, 2002; Weber, Wilkerson, & Reinhardt, 2004), but there is generally a stronger correlation between organic matter and sorption than clay content and sorption (Kookana et al., 1998; Weber et al., 2004). In addition, although organic matter and clay content have a dominant influence on sorption, pH may also affect sorption (Fontecha-Cámara et al., 2007). A decrease in pH may affect the sorption of an ionic herbicide such as atrazine, but pH may not have a direct effect on the sorption of a neutral, non-ionic molecule such as diuron (Fontecha-Cámara et al., 2007; Liyanage et al., 2006). However, although the pH of the sandy silt loam may have altered (reduced) the sorption of atrazine in this soil, the equally low sorption in the loam soil (at higher pH) and higher sorption observed in the clay loam suggests that the variations in pH of the soils used in this study are too small to explain the difference in sorption between soils.

As observed in this study, the antibiotics had a higher sorption to soil than the herbicides. Because both antibiotics and herbicides depend on soil organic matter for
sorption, it may be speculated that there is competition for surface reactions. Sonon and Schwab (1995) have reported much higher $K_d$ values for atrazine as compared to the $K_d$ values of this study, suggesting that in this study there may have been competition for surface reactions.

### 4.2 Biochar sorption

Rice husk's ability to sorb the agrochemicals could be explained with regard to its aromaticity and ash content. The low O/C and H/C ratios of the rice husk biochar as compared to the other biochars showed that rice husk biochar had a higher level of aromaticity and carbonization. The biochar molar H/C ratios of $\leq 0.3$ indicate a highly condensed aromatic ring system (Vithanage et al., 2016). A high level of aromaticity provides an advantage for sorption of agrochemicals (Li, Li, Wu, Zhang, & Li, 2013). Furthermore, rice husk biochar exhibited a higher ash content as compared to miscanthus and softwood biochars in this study. The high ash content of the rice husk biochar was possibly due to the high presence of lignin (Vithanage et al., 2016). The ash content consists of hydroxyl groups, which are the main contributors to the adsorption mechanism. Yang et al. (2006) have shown that rice residue biochars with high ash content were more effective in absorbing herbicides such as diuron. Furthermore, although softwood biochar had a low ash content, it had a higher surface area (see Table 2). It could therefore be assumed that softwood biochar would be better at sorbing the agrochemicals than rice husk and miscanthus straw biochar. Yavari, Malakahmad, and Sapari (2015) also explain that when biochars have a low ash content, there is less opportunity for the biochar's surface area to be blocked by the ash. When comparing the sorption coefficient of the herbicides and antibiotics in this study, the antibiotics had a higher sorption coefficient than atrazine (see Table 4). As previously discussed in the soil sorption experiments, Site (2000) suggested that due to the monofunctional nature of the sorbent and the antibiotic's strong intermolecular attraction and ability to penetrate into absorbent layers, antibiotics had a higher sorption coefficient than herbicides. Although desorption hysteresis was not measured in this study, agrochemicals could exhibit desorption hysteresis on biochars characterized by higher specific surface areas (Bryan, 1987).

### 4.3 Biochar-amended soil sorption

When applied to soil, the agrochemical fate is determined by mixing/dissolution in the soil water, sorption onto soil particles, microbial degradation, and partitioning into gas phase and volatilization into the air, therefore posing a potential soil, air and water pollution risk (Liyanage et al., 2006; Bedmar et al., 2017; Pan & Chu, 2017a). By amending soils with biochar, agrochemical leaching and volatilization can be reduced by mechanisms such as increased agrochemical sorption, which retains agrochemicals in the bioactive topsoil layer for microbial degradation. Amendment of the soil by rice husk biochar applied at rates between 1% and 5% (w/w) could cause significant changes to the soil. These changes include pH, cation exchange capacity, organic carbon, hydrological properties and bulk density (Gamage et al., 2016). Although some antibiotics were non-detectable even without biochar amendment, where antibiotics were observed in the aqueous phase in the soil sorption study, these additional experiments indicated that a soil amendment of 1% (w/w) rice husk biochar could be sufficient to further reduce the risk of some antibiotic leaching. Furthermore, without the presence of biochar in the soils, antibiotics are potentially capable of reducing the microbial population, specifically, the natural bacterial community in the soil. Reducing the microbial population in the soil could hinder microbial biodegradation of herbicides in the soil. Liu et al. (2020) and Duan et al. (2017) suggested that the application of biochar could promote the growth of the soil microbial community by providing space and retaining nutrients in the soil, thus increasing the opportunity for microbial biodegradation of herbicides to occur in the soil. Furthermore, Duan et al. (2017) explained that biochar's micropores could increase water retention and increase the passage of light within the soil, therefore increasing the hydrolysis and photolysis of antibiotics such as oxytetracycline. Furthermore, Duan et al. (2017) also explained that the addition of biochar could reduce both antibiotic-resistant genes and human bacterial pathogens, reducing the harmful effects of antibiotics on human health. However, careful attention must also be given to the effects of ageing on biochar's ability to sustain the sorption of the antibiotics (He et al., 2019).

With regard to herbicides, biochar-amended soil sorption was due to a combination of both biochar and soil properties. However, biochar was more dominant in sorbing the agrochemicals than soil. The increase in biochar dosages in the soil clearly showed that the absorption coefficient was also increased. As compared to all of the agrochemicals, atrazine was the only agrochemical that was detected, even with a 5% (w/w) biochar-soil amendment. There are several reasons why 5% (w/w) biochar amendment could not completely absorb atrazine. Firstly, because all of the antibiotics along with diuron were entirely absorbed by the biochar-amended soil at
2.5 and 5\% (w/w), there may have been competition between atrazine, diuron and the antibiotics for sorption sites throughout the biochar-amended soil matrix. Secondly, because biochar by itself had higher absorption capability for the agrochemicals than the soils, the biochar was the dominant sorbent for the compounds. Therefore, when biochar is mixed with soil, it is possible that the dissolved organic matter from the soil may act as a coating over the biochar absorption sites, thus blocking the herbicides from binding to the biochar absorption sites (Ahmad et al., 2014). Biochar being blocked by the dissolved organic matter was also observed in the study by Cao, Ma, Gao, and Harris (2009), where higher dissolved organic matter had reduced atrazine absorption due to pore and absorption site blockage. Furthermore, the biochar-amended soil had a higher absorption coefficient than soil without biochar amendment, indicating that biochar-amended soils could reduce agrochemical leaching in the soil.

4.4 Environmental fate modelling

The modelling presented takes our understanding of the sorptive capacity of rice husk biochar on atrazine gained from the batch sorption studies and applies it to a real-world risk assessment scenario. Biochar may be applied to the soil surface or incorporated into the soil during tillage. We did not explore the use of biochar as a layer in the model, as there are issues with the use of biochar in this way, such as rapid loss via erosion (e.g., wind) or run-off, health and safety concerns and high costs (Shackley et al., 2012). However, biochar amendment via soil incorporation does not suffer from the same concerns and may be a more appropriate/realistic way of using biochar to mitigate the loss of agrochemicals to groundwater and as such was modelled. The results of the modelling clearly demonstrated a significant reduction in the predicted concentrations of atrazine in groundwater following the incorporation of biochar in the soil. This demonstrates that biochar may be an effective tool for reducing leaching of agrochemicals. However, the modelling results showed some added complexity, with lower levels of biochar amendment resulting in lower PECgw than when adding higher levels of biochar. This appears counterintuitive, given that biochar contains a higher percentage of organic material and therefore more of it would bind more atrazine. However, the biochar also alters the hydrology of the soil, with the lower bulk density of biochar potentially leading to increased flow through soil pores and increased leaching, as reflected in the literature (Glab, Palmowska, Zaleski, & Gondek, 2016). There is in effect, a trade-off between sorping more agrochemical to reduce leaching and not compromising soil integrity, leading to increased leaching. This trade-off makes it difficult to generalize the benefit of biochar in mitigating agrochemical leaching in all cases and, as such, we identify that biochar amendment appears a potentially effective tool to mitigate leaching, whilst cautioning against a generalization that all biochar will act to mitigate the risk from leaching in all cases.

5 CONCLUSIONS

This study determined the effects of rice husk, miscanthus and softwood biochar types upon absorption of atrazine, diuron, enrofloxacine, oxytetracycline and tetracycline. The sorption varied with biochar, agrochemical and soil type. According to our results, the rice husk biochar had the highest absorption capacity for all of the agrochemicals. Rice husk biochar was characterized by the lowest O/C and H/C levels and highest ash content, which made it the best absorbent for all the agrochemicals. Biochar-amended soils had better absorption for the agrochemicals than soils without biochar amendment. Our modelling demonstrated a significant reduction in PECgw in scenarios with biochar-amendment; however, there is a trade-off between the sorptive potential of biochar to reduce leaching and the changes in soil properties that may inadvertently lead to increased leaching. Our study suggests that applying biochar to tropical soils of Belize could reduce agrochemical contamination of soil and water, although the implementation should be conducted carefully, taking account of the potential trade-offs with biochar use identified in our modelling. These findings are especially important because atrazine has been a problematic agrochemical in tropical regions due to its persistence in groundwater. However, field studies are needed to determine the long-term effects of biochar-amended soils on the fate of agrochemicals.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

DATA AVAILABILITY

Data available in article supplementary material The data that supports the findings of this study are available in the supplementary material of this article.
REFERENCES
Ahmad, M., Rajapaksha, A. U., Lim, J. E., Zhang, M., Bolan, N., Mohan, D., ... Ok, Y. S. (2014). Biochar as a sorbent for contaminant management in soil and water: A review. Chemosphere, 99, 19–33.
Ahmed, M. B., Zhou, J. L., Ngo, H. H., Guo, W., Johir, M. A. H., & Sornalingam, K. (2017). Single and competitive sorption properties and mechanism of functionalized biochar for removing sulfonamide antibiotics from water. Chemical Engineering Journal, 311, 348–358.
Baskaran, S. (1994). Sorption and movement of ionic and non-ionic pesticides in selected soils of New Zealand. Massey University. Palmerston North, New Zealand. Retrieved from http://mro.massey.ac.nz/bitstream/10179/3079/1/02_whole.pdf.
Bedmar, F., Gimenez, D., Costa, J. L., & Daniel, P. E. (2017). Persistence of acetochlor, atrazine, and s-metolachlor in surface and sub-surface horizons of 2 typic argiudolls under no-tillage. Environmental Toxicology and Chemistry, 36, 3065–3073.
Beesley, L., Moreno-Jiménez, E., Gomez-Eyles, J. L., Harris, E., Robinson, B., & Szimur, T. (2011). A review of biochars’ potential role in the remediation, revegetation and restoration of contaminated soils. Environmental Pollution, 159, 3269–3282.
Bryan, W. P. (1987). Sorption hysteresis and the laws of thermodynamics. Journal of Chemical Education, 64, 209.
Cao, X. D., Ma, L. N., Gao, B., & Harris, W. (2009). Dairy-manure derived biochar effectively sorbs lead and atrazine. Environmental Science & Technology, 43, 3285–3291.
Carter, S., Shackley, S., Sohi, S., Suy, T., & Haefele, S. (2013). The impact of biochar application on soil properties and plant growth of pot grown lettuce (Lactuca sativa) and cabbage (Brassica chinensis). Agronomy, 3, 404–418.
Carvalho, I. T., & Santos, L. (2016). Antibiotics in the aquatic environments: A review of the European scenario. Environment International, 94, 736–757.
Cederlund, H., Börjesson, E., & Stenström, J. (2017). Effects of a wood-based biochar on the leaching of pesticides chlorpyrifos, diuron, glyphosate and MCPA. Journal of Environmental Management, 191, 28–34.
Chaukura, N., Gwenzi, W., Tavengwa, N., & Manyuchi, M. M. (2016). Biosorbents for the removal of synthetic organics and emerging pollutants: Opportunities and challenges for developing countries. Environ Develop, 19, 84–89.
Chicas, S. & Omine, K. (2015). Forest cover change and soil erosion in Toledo’s Rio Grande watershed. ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XL-7/W3, 353–358. Retrieved from http://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XL-7/W3/353/2015/
Dari, B., Nair, V. D., Harris, W. G., Nair, P. K. R., Sollenberger, L., & Mylavaramu, R. (2016). Relative influence of soil vs. biochar properties on soil phosphorus retention. Geoderma, 280, 82–87.
Deng, H., Feng, D., He, J., Li, F., Yu, H., & Ge, C. j. (2017). Influence of biochar amendments to soil on the mobility of atrazine using sorption-desorption and soil thin-layer chromatography. Ecological Engineering, 99, 381–390.
Duan, M., Li, H., Gu, J., Tao, X., Sun, W., Qian, X., & Wang, X. (2017). Effects of biochar on reducing the abundance of oxytetracycline, antibiotic resistance genes, and human pathogenic bacteria in soil and lettuce. Environmental Pollution, 224, 787–795.
FOCUS, (2000). FOCUS groundwater scenarios in the EU review of active substances. EC Document Reference Sanco/321/2000 version 1, rev. 2, (202 pp).
FOCUS, (2014). Assessing Potential for Movements of Active Substances and their Metabolites to Ground Waters in the EU. EC Document Reference Sanco/13144/2010 version 3, 613pp.
Fontecha-Cámara, M. A., López-Ramón, M. V., Álvarez-Merino, M. A., & Moreno-Castilla, C. (2007). Effect of surface chemistry, solution pH, and ionic strength on the removal of herbicides diuron and amitrole from water by an activated carbon fiber. Langmuir, 23, 1242–1247.
Gamage, D. N. V., Mapa, R. B., Dharmakeerthi, R. S., & Biswas, A. (2016). Effect of rice-husk biochar on selected soil properties in tropical alfisols. Soil Research, 54, 302–310.
Gláb, T., Palmowska, J., Zaleski, T., & Gondek, K. (2016). Effect of biochar application on soil hydrological properties and physical quality of sandy soil. Geoderma, 281, 11–20.
Hamill, A. S., & Zhang, J. (1997). Rate and time of bentazon/atrazine application for broadleaf weed control in corn. Weed Science Society of America, 11(3), 549–555.
He, Y., Liu, C., Tang, X., Xian, Q., Zhang, J., & Guan, Z. (2019). Biochar impacts on sorption-desorption of oxytetracycline and florfenicol in an alkaline farmland soil as affected by field ageing. Science of the Total Environment, 671, 928–936.
Huang, D., Wang, X., Zhang, C., Zeng, G., Peng, Z., Zhou, J., ... Qin, X. (2017). Sorptive removal of ionizable antibiotic sulfamethazine from aqueous solution by graphene oxide-coated biochar nanocomposites: Influencing factors and mechanism. Chemosphere, 186, 414–421.
Inoue, M. H., Oliveira, R. S., Regitano, J. B., Tormena, C. A., Constantín, J., & Tornisielo, V. L. (2004). Sorption kinetics of atrazine and diuron in soils from southern Brazil. Journal of Environmental Science and Health - Part B Pesticides, Food Contaminants, and Agricultural Wastes, 39, 589–601.
Joseph, S. D., Camps-Arbestain, M., Lin, Y., Munroe, P., Chia, C. H., Hook, J., ... Amonette, J. E. (2010). An investigation into the reactions of biochar in soil. Australian Journal of Soil Research, 48, 501–515.
Kemper, N. (2008). Veterinary antibiotics in the aquatic and terrestrial environment. Ecological Indicators, 8, 1–13.
Kim, S. H., Fan, M., Prasher, S. O., Patel, R. M., & Hussain, S. A. (2011). Fate and transport of atrazine in a sandy soil in the presence of antibiotics in poultry manures. Agricultural Water Management, 98, 653–660.
Kookana, R. S. (2010). The role of biochar in modifying the environmental fate, bioavailability, and efficacy of pesticides in soils: A review. Australian Journal of Soil Research, 48, 627–637.
Kookana, R. S., Baskaran, S., & Naidu, R. (1998). Pesticide fate and behaviour in Australian soils in relation to contamination and management of soil and water: A review. Australian Journal of Soil Research, 36, 715.
Lewis, K. A., Tzilivakis, J., Warner, D., & Green, A. (2016). An international database for pesticide risk assessments and
management. *Human and Ecological Risk Assessment: An International Journal*, 22(4), 1050–1064.

Li, J., Li, Y., Wu, M., Zhang, Z., & Li, J. (2013). Effectiveness of low-temperature biochar in controlling the release and leaching of herbicides in soil. *Plant and Soil*, 370, 333–344.

Liu, H., Song, C., Zhao, S., & Wang, S. (2020). Biochar-induced migration of tetracycline and the alteration of microbial community in agricultural soils. *Science of the Total Environment*, 706, 136086.

Liyanage, J. A., Watawala, R. C., Aravinna, A. G. P., Smith, L., & Naidu, R., & Kim, K. R. (2008). Contaminant fate, dynamics and management. *Human and Ecological Risk Assessment: An International Journal*, 22(4), 1050–1064.

Manna, S., Singh, N., & Singh, S. B. (2018). In-vitro evaluation of rice and wheat straw biochars’ effect on pyrazosulfuron-ethyl degradation and microbial activity in rice-planted soil. *Soil Research*, 56, 579–587.

Mrozik, W., Vinithnantharat, S., Thongsamer, T., Pansuk, N., Pattanachan, P., Thayanukul, P., ... Werner, D. (2019). The food-water quality nexus in periurban aquacultures downstream of Bangkok, Thailand. *Science of the Total Environment*, 695, 133923.

Naidu, R., & Kim, K. R. (2008). Contaminant fate, dynamics and bioavailability: Biochemical and molecular mechanism at the soil: Root interface. *Revista de la Ciencia del Suelo y nutrición Vegetal*, 8, 56–63.

Nemeth-Konda, L., Füleky, G., Morovjan, G., & Csokan, P. (2002). Sorption behaviour of acetochlor, atrazine, carbendazim, diazinon, imidacloprid and isoproturon on Hungarian agricultural soil. *Chemosphere*, 48, 545–552.

Obia, A., Cornelissen, G., Mulder, J., & Dörsch, P. (2015). Effect of soil pH increase by biochar on NO, N₂O and N₂ production during denitrification in acid soils. *PLoS One*, 10, 1–19.

OECD. (2000). OECD 106 adsorption - desorption using a batch equilibrium method. OECD guideline for the testing of chemicals, 1–44. Retrieved from http://www.oecd-ilibrary.org/environment/test-no-106-adsorption-desorption-using-a-batch-equilibrium-method_9789264069602-en.

Pan, M., & Chu, L. M. (2017a). Fate of antibiotics in soil and their uptake by edible crops. *Science of the Total Environment*, 599–600, 500–512.

Pan, M., & Chu, L. M. (2017b). Leaching behavior of veterinary antibiotics in animal manure-applied soils. *Science of the Total Environment*, 579, 466–473.

Queyrel, W., Habets, F., Blanchoud, H., Ripoche, D., & Launay, M. (2016). Pesticide fate modeling in soils with the crop model STICS: Feasibility for assessment of agricultural practices. *Science of the Total Environment*, 542, 787–802.

Samuelsen, O. B., Torsvik, V., & Ervik, A. (1992). Long-range changes in oxytetracycline concentration and bacterial resistance towards oxytetracycline in a fish farm sediment after medication. *Science of the Total Environment*, 114, 25–36.

Sengelov, G., Agerø, Y., Halling-Sørensen, B., Baloda, S. B., Andersen, J. S., & Jensen, L. B. (2003). Bacterial antibiotic resistance levels in Danish farmland as a result of treatment with pig manure slurry. *Environment International*, 28, 587–595.

Shackley, S., Carter, S., Knowles, T., Middelink, E., Haefele, S., Sohi, S., ... Haszeldine, S. (2012). Sustainable gasification-biochar systems? A case-study of rice-husk gasification in Cambodia, part i: Context, chemical properties, environmental and health and safety issues. *Energy Policy*, 42, 49–58.

Singh, B., MacDonald, L. M., Kookana, R. S., Van Zwieten, L., Butler, G., Joseph, S., ... Esfandbod, M. (2014). Opportunities and constraints for biochar technology in Australian agriculture: Looking beyond carbon sequestration. *Soil Research*, 52, 739–750.

Site, A. D. (2000). Factors affecting sorption of organic compounds in natural sorbent / water systems and sorption coefficients for selected pollutants. *Journal of Physical and Chemical Reference Data*, 30, 2001.

Sonon, L., & Schwab, A. P. (1995). Adsorption characteristics of atrazine and alachlor in Kansas soils. *Weed Science*, 43, 461–466.

Tolls, J. (2001). Sorption of veterinary pharmaceuticals in soils: A review. *Environmental Science and Technology*, 35, 3397–3406.

Trinh, B. S., Werner, D., & Reid, B. J. (2017). Application of a full-scale wood gasification biochar as a soil improver to reduce organic pollutant leaching risks. *Journal of Chemical Technology and Biotechnology*, 92, 1928–1937.

Vithanage, M., Mayakaduwa, S. S., Herath, I., Ok, Y. S., & Mohan, D. (2016). Kinetics, thermodynamics and mechanistic studies of carbofuran removal using biochars from tea waste and rice husks. *Chemosphere*, 150, 781–789.

Weber, J. B., Wilkerson, G. G., & Reinhardt, C. F. (2004). Calculating pesticide sorption coefficients (Kd) using selected soil properties. *Chemosphere*, 55, 157–166.

Worrall, F., Parker, A., Rae, J. E., & Johnson, A. C. (1997). A study of the adsorption kinetics of isoproturon on soil and subsoil. *Chemosphere*, 34, 71–86.

Wu, T. H., Rainwater, T. R., Platt, S. G., McMurry, S. T., & Anderson, T. A. (2000). DDE in eggs of two crocodile species from Belize. *Journal of Agricultural and Food Chemistry*, 48, 6416–6420.

Yang, Y., Sheng, G., & Huang, M. (2006). Bioavailability of diuron in soil containing wheat-straw-derived char. *Science of the Total Environment*, 354, 170–178.

Yao, H., Lu, J., Wu, J., Lu, Z., Wilson, P. C., & Shen, Y. (2013). Adsorption of fluoroquinolone antibiotics by wastewater sludge biochar: Role of the sludge source. *Water, Air, and Soil Pollution*, 224, 1370–1377.

Yavari, S., Malakahmad, A., & Sapari, N. B. (2015). Biochar efficiency in pesticides sorption as a function of production variables—A review. *Environmental Science and Pollution Research*, 22, 13824–13841.

Zhelezova, A., Cederlund, H., & Stenström, J. (2017). Effect of biochar amendment and ageing on adsorption and degradation of two herbicides. *Water, Air, and Soil Pollution*, 228, 216.

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