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Impact of Atrazine and Biochar Pre-treatment on Soil and Leachate Properties

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ABSTRACT

Atrazine is a widely used herbicide in agriculture, but its persistence and mobility in soils and water pose ecological and health risks, however, biochar a carbon rich solid product of biomass pyrolysis, has been proposed as a strategy to reduce herbicide leaching and improve soil quality. This study assessed the effects of atrazine application (at manufacturers, adjusted lower and higher rates of 3.0, 1.5 and 4.5 kg of the active ingredients ha^{-1} and biochar pre-treatment (*Tithonia diversifolia*, TD and TD + bonemeal, applied at 3 t ha^{-1}) on soil and leachate properties in soils with contrasting organic carbon contents. A factorial leaching column experiment was conducted with 72 experimental units, using 250 g soil columns under screen-house conditions. Results revealed that , Nitrate leaching reached 9.7 mg L^{-1} in LOC compared to 8.9 mg L^{-1} in high organic carbon (HOC) soils, while phosphate losses ranged from 0.00 to 0.35 mg L^{-1}. Biochar amendments enhanced soil quality by increasing organic carbon (up to 3.32%) and available phosphorus (up to 105.3 mg kg^{-1}), but this led to short-term nutrient leaching, with leachate electrical conductivity (EC) rising to 1780 µS cm^{-1} in amended HOC soils compared to 664 µS cm^{-1} in the control. Overall, biochar, particularly TD + bonemeal, reduced atrazine mobility and improved soil fertility, though its effectiveness was soil-dependent and required careful rate management to minimize leaching risks.

Keywords: *Atrazine, Biochar, Soil organic carbon, Leaching*

INTRODUCTION

Herbicides play an integral role in modern agriculture, providing efficient weed control and sustaining crop productivity (Marcato *et al,* 2017). Among them, atrazine, a chlorinated triazine and photosystem II (PSII) inhibitor, is one of the most widely used because of its broad-spectrum control of both broadleaf and grassy weeds, particularly in major crops such as maize, sorghum, and sugarcane (Yang *et al,* 2021; Vizioli *et al,* 2023). However, atrazine's persistence in soil (half-life ranging from 13 to 261 days) and tendency to migrate into groundwater raise significant ecological and public health concerns (U.S. EPA, 2003; Zhao *et al*, 2023). Atrazine residues have been detected in surface water and groundwater worldwide, threatening aquatic ecosystems and drinking water safety (Giddings *et al*, 2023).

Soil organic matter (SOM) strongly influences the fate of atrazine, higher SOM enhances its sorption and reduces mobility, thereby affecting its persistence and availability in soils (Fiore *et al*, 2022; Wang *et al*, 2023). High organic carbon soils adsorb atrazine, reducing its bioavailability and mobility, while low organic carbon soils promote leaching and persistence (Smith *et al*, 2020; Rodríguez-Camacho *et al*, 2021). The ecological impact is further compounded by atrazine's effect on soil microbial diversity, respiration, and enzyme activity (Singh *et al*, 2023).

To mitigate these risks, soil amendments such as lime, phosphate, and biochar have been explored (Xu *et al*, 2020). Biochar, a carbon-rich solid product derived from biomass pyrolysis, enhances soil structure and functionality by improving porosity, cation exchange capacity (CEC), and water retention, while also reducing herbicide mobility and bioavailability (Xie *et al*, 2024; Aldana *et al*, 2024) Recent studies confirm biochar's effectiveness in adsorbing contaminants and stimulating microbial degradation (Kolton *et al*, 2017; Yavari *et al*, 2022).

This study investigated the combined effects of atrazine with and without biochar pre-treatment on selected soil and leachate properties.

Materials and Methods

Soil Sampling

Two soils with contrasting organic carbon contents were studied. Low organic carbon (LOC) soil was collected from arable land at the Teaching and Research Farm, Ladoke Akintola University of Technology (LAUTECH), Ogbomoso Oyo state, while high organic carbon (HOC) soil was obtained from a woodlot near Olusegun Oke Library, LAUTECH, Ogbomoso, Oyo State,Nigeria Located in the Derived Southern Guinea savannah agro-ecological zone of Nigeria located on 8°10′N latitude and 4°10′E longitude. Soils were sampled at 0–15 cm depth, air-dried, crushed, sieved (2 mm) and subjected to initial physico-chemical characterization following standard laboratory procedures.

Biochar Production

The biochar studied was produced from dried *Tithonia diversifolia* (TD) biomass, with and without bone meal (BM), at 350 °C for 15 minutes resident time to give sole TD (tagged B1) and TD + bonemeal (tagged B2). The biochar were pulverized, and stored in an air tight polyethylene bags. TD biochar was designated **B1**, and TD + BM biochar was designated **B2**.

Treatments and Experimental Design

A leaching column experiment was established using a completely randomized design (CRD). Treatments consisted of three atrazine application rate (lower rate (tagged Atr L), manufacturer's rate (tagged Atr M) and higher rate (tagged Atr H) with and without biochar (B1, B2) pre-treatment applied to both LOC and HOC soils. Each treatment was replicated three times, to give 72 experimental units.

Experimental Setup

Polyvinyl chloride (PVC) pipes (23 cm height, 4 cm inner diameter) were used as leaching columns. Each was filled with 250 g of 2 mm sieved soil, lined at one end with a triple-fold nylon mesh placed over a leachate collection cup. Biochar was applied at 5 t/ha (0.63 g per 250 g soil) and mixed within the top 5 cm soil depth. Preliminary trials estimated 60 and 87 ml of water respectively needed to take the LOC and HOC soil to field capacity. The biochar was thereafter left to equilibrate in each column for two weeks. This was followed by atrazine application in appropriate leaching columns along side basal NPK 15-15-15 application at 60 kgN/ha (equivalent to 0.03 g/250g soil). The whole setup was kept covered with aluminum foil under screen house condition. Leaching was simulated using drip application of distilled water at 80 ml per column a week after agrochemical application. The experiment was a factorial combination of three atrazine application rates, two soil types with or without two biochar pre-treatment, soils that received rather atrazine and biochar were included for comparison. Each treatment was replicated three times to give 72 experimental unit. The treatment summary is giving thus:

Sole atrazine applied at manufacturer's rate of 3.0 kg a.i/ha equivalent to 0.38 µkg/250g soil (tagged Atr M)
Atrazine applied at manufacturer's rate with type 1 biochar (tagged Atr M + B1)
Atrazine applied at manufacturer's rate with type 2 biochar (tagged Atr M + B2)
Sole atrazine applied at higher rate of 4.5 kg a.i/ha equivalent to 0.56 µkg/250g soil (tagged Atr H)
Atrzine applied at higher rate with type 1 biochar (tagged Atr H + B1)
Atrzine applied at higher rate with type 2 biochar (tagged Atr H + B2)
Sole atrazine at lower rate of 1.5 kg a.i/ha equivalent to 0.19 µkg/250g soil (tagged Atr L)
Atrazine applied at lower rate with type 1 biochar (tagged Atr L + B1)
Atrazine applied at lower rate with type 2 biochar (tagged Atr L + B2)
Sole biochar type 1 (B1)
Sole Biochar type 2 (B2)
Absolute Control that will receive neither herbicide nor biochar (tagged AC)

The leachate collected were stored in plastic sampling bottles at 4 ^{0}c prior to lab leachate properties evaluation. Maize was thereafter sown at one plant per column and nurtured for three weeks. Post harvest soil sampling was carried out in each column and the soil were prepared for laboratory analyses

Data Collection

Volume of leachate collected per treatment was taken using a measuring cylinder, immediately after collection the leachate collected were subjected to pH, electrical conductivity EC, Total dissolved solid TDS, NO_3^- N and PO_4 content determination following standard procedure. Calibrated pH, EC and TDS meter were utilized for the determination of the leachate pH, EC and TDS. The UV spectrophotometric was used for the determination of NO_3^- N content in the leachate after digestion with KCl while the molybdenum blue colorimetric method was followed for PO_4 leachate content determination after ascorbic acid reduction.

The soil sampled from each leaching column after maize harvesting were subjected to pH, EC, Organic carbon and available P determination. The pH and EC were determined from soil and distilled water mixture at ratio 1:2 using earlier calibrated pH and EC meter. The walkey black procedure was followed for organic carbon determination while mehlich - 3 extractant was utilized for available P extraction from the soil.

Statistical Analysis

Data collected were subjected to ANOVA using Gensat statistical package, and treatment means values generated were separated using LSD at significant level of 5%.

Results and Discussions

Characteristics of the experimental soil and tested biochar

The characteristics of experimental soil is shown in Table 1, the low organic carbon (LOC) soil was slightly alkaline (pH 7.59) with low electrical conductivity (183.69 µS cm^{-1}), depleted in organic carbon (0.73%), and relatively higher in total nitrogen (0.62 g kg^{-1}) compared with the high organic carbon (HOC) soil with 1.44 % organic carbon and 0.21 g kg^{-1} total nitrogen TN. The LOC soil also had lower concentrations of exchangeable bases (Ca = 2.85, Mg = 0.62, K = 0.13, Na = 0.09 cmol kg^{-1}) and available phosphorus (5.86 mg kg^{-1}). In contrast, the HOC soil was slightly alkaline (pH 7.24) with higher electrical conductivity (306.57 µS cm^{-1}), greater organic carbon (1.44%), and higher levels of Ca (9.23 cmol kg^{-1}), Mg (1.58 cmol kg^{-1}), K (0.27 cmol kg^{-1}), Na (0.34 cmol kg^{-1}), and available phosphorus (7.75 mg kg^{-1}). Texturally, the LOC soil had a higher clay content (120 g kg^{-1}) compared with HOC (37 g kg^{-1}), while the HOC soil was sandy. Overall, the LOC soil was more nutrient-depleted but finer-textured, whereas the HOC soil was richer in organic matter and bases but coarser-textured.

Characteristics of biochar tested

Table 2 shows the characteristics of biochar tested. Significant differences were observed between the two biochars tested, B1 and B2, across all measured parameters. Ash content was higher in B2 (84.7%) compared to B1 (20.04%), representing more than a 320% increase. Both biochars were strongly alkaline, with B1 showing a slightly higher pH (10.86) than B2 (10.52). Electrical conductivity (EC) was greater in B1 (6.35 mS/cm), which was more than double the value recorded for B2 (3.05 mS/cm). Carbon content was dominant in B1 (58.7%), exceeding B2's value (14.41%) by over 300%, while nitrogen content followed a similar trend with B1 (1.07%) higher than B2 (0.84%). Conversely, phosphorus was relatively low in both biochars but slightly higher in B2 (0.07%) than B1 (0.02%). Potassium content was greater in B1 (0.42%) compared to B2 (0.28%), while calcium levels were higher in B2 (0.32%) than B1 (0.17%).

Table 1. Selected characteristics of the soil studied

PARAMETERS	VALUES	
	LOC	HOC
pH (H2O)	7.59	7.24
EC (µs/cm)	183.69	306.57
Available P (mehlich) Total	5.86	7.75
N (g/kg)	0.62	0.21
Organic C (%)	0.73	1.44
Ex. Cations (cmol/kg)		
Ca	2.85	9.23
Mg	0.62	1.58
K	0.13	0.27
NA	0.09	0.34
Particle Size (g/kg)		
Sand	780	889
Silt	100	74
Clay	120	37

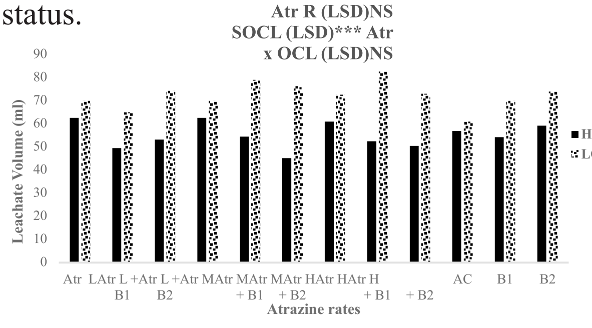
Table 2: characteristics of the biochar studied

Biochar parameters	B1	B2
Ash (%)	20.04	84.7
pH	10.86	10.52
EC (mS/cm)	6.35	3.05
C (%)	58.7	14.41
N (%)	1.07	0.84
P (%)	0.02	0.07
K (%)	0.42	0.28
Ca (%)	0.17	0.32

Effects of different atrazine rates in soil with contrasting organic carbon content on leachate volume

The effects of different atrazine rates in soils with contrasting organic carbon content on leachate volume is shown in Fig. 1. Leachate volume was significantly influenced by soil organic carbon (OC) content but not by the different atrazine rate. Leachate volume ranged from 49.3 ml (in Atr L + B1) to 62.3 ml (in Atr L and Atr M) in HOC

soil while a range of 69.7 ml (in Atr L and Atr M) to 82.3 ml (in Atr H + B1) was observed in LOC soil. Atrazine alone did not alter leachate volume significantly compared with AC (58.7 ml). For instance, Atr L and Atr M averaged 66.0 ml, a marginal increase of 12% relative to AC, while Atr H recorded 66.5 ml (13% higher).
Biochar-modified treatments altered volumes differently depending on OC level. In HOC soils, B1 and B2 reduced leachate volumes by 7–20% compared to atrazine-only soils. In LOC soils, B1 and B2 increased leachate volumes by 6–19%. The highest volume (82.3 ml) occurred in LOC soils under Atr H + B1, a 35% increase compared to AC. Sole biochar treatments (B1 and B2) produced moderate leachate volumes (61.8–66.2 ml), 5–13% higher than AC (58.7 ml).
This observation indicates that biochar benefits water retention in high SOM soils, but in low SOM systems it may accelerate water fluxes due to incomplete stabilization of fresh biomass. These findings support Mukherjee and Lal (2013), who showed biochar enhances water retention and lowers leachate in organic-rich soils, while Niemeyer et al, (2023) reported higher drainage volumes in low-SOM soils under herbicide treatments. The divergence in effects between HOC and LOC soils is consistent with Lehmann et al (2011), who stressed soil carbon status as key to biochar performance. Similarly, Tejada et al (2011) observed that organic amendments can improve structure in fertile soils but destabilize water balance in degraded soils. Overall, atrazine alone had little effect on leachate, but biochar's impact was strongly conditioned by soil OC status.



Atr= Atrazine, Atr R= Atrazine rate, Atr L= Atrazine at lower rate, Atr M= Atrazine at manufacturer's rate, Atr H= Atrazine at higher rate, B1= sole *Tithonia diversifolia,* B2= *Tithonia diversifolia* + Bonemeal, SOCL= Soil organic carbon level, AC= Absolute control, HOC= High organic carbon soil, LOC= Low organic carbon soil, LSD= least significant mean at 5%.

Effects of different atrazine rates in soils with contrasting organic carbon content on leachate and soil pH

The effects of different atrazine rates and organic carbon levels on leachate and soil pH are presented in Table 3. The leachate pH was significantly influenced by atrazine rate ($p < 0.01$) and soil organic carbon (OC) level ($p < 0.001$), while their interaction was not significant. Leachate pH values ranged from 7.21 (in Atr M) to 7.68 (in Atr H + B2) in LOC while a range of 7.85 (in Atr H) to 8.35 (in Atr L + B2) was observed in HOC. The LOC soil consistently produced less alkaline leachate conditions, averaging around 7.3, compare to more alkaline leachate, averaging near 8.0 in HOC soil. Soil pH was significantly affected by atrazine rates, SOC level, and their interaction ($p < 0.001$), with values spanning from 6.78 (in Atr M + B1, HOC) to 7.61 (in Atr M + B2, LOC).Atrazine application alone resulted in a 2–4% reduction in soil pH relative to the absolute control (AC, 7.24). In contrast, the incorporation of biochar (B1 and B2) moderated this effect by raising soil pH by 2–5% above AC. The highest pH was observed in Atr M + B2 (7.41), representing a 2.3% increase over AC. Sole biochar treatments (B1 and B2) also maintained soil pH near neutrality (7.35–7.42), confirming their consistent liming effect.

The acidifying trend observed can be attributed to the production of weak organic acids during atrazine degradation. These results are consistent with the findings of Kabir *et al* (2023), who reported that biochar effectively neutralized acidity and elevated soil pH in atrazine-contaminated soils. Likewise, Udomkun *et al* (2025) observed that biochar amendments buffered herbicide-induced acidification, reinforcing the protective and pH-stabilizing capacity of biochar observed in this study. Overall, atrazine alone slightly acidified soils, but biochar effectively counteracted this effect, particularly in high-organic-carbon soils where the buffering capacity was greatest.

Table 3 Effects of different atrazine rates in soils with contrasting organic carbon content on leachate and soil pH

	Leachate pH			Soil pH		
	Soil organic carbon level			Soil organic carbon level		
Atrazine Rates	HOC	LOC	Mean	HOC	LOC	Mean
Atr L	8.06	7.32	7.69	7.10	7.07	7.09
Atr L + B1	7.88	7.34	7.61	6.92	7.19	7.05
Atr L + B2	8.35	7.46	7.90	7.22	7.19	7.20
Atr M	7.93	7.21	7.57	7.11	7.31	7.21
Atr M + B1	8.02	7.36	7.69	6.78	7.39	7.09
Atr M + B2	8.21	7.35	7.78	7.20	7.61	7.41
Atr H	7.85	7.29	7.57	7.02	7.43	7.22
Atr H + B1	8.23	7.32	7.77	7.17	7.08	7.13
Atr H + B2	8.03	7.68	7.85	7.03	7.04	7.04
Mean	8.63	7.37		7.06	7.26	
Atr R(LSD)	**			***		
SOCL (LSD)	***			***		
Atr R x SOCL (LSD)	NS			***		

Checks AC						
B1	7.82	7.42	7.62	7.24	7.59	7.42
B2	7.71	7.62	7.67	7.20	7.50	7.35
	7.91	7.90	7.71	7.39	7.26	7.32

Atr= Atrazine, Atr L= Atrazine at lower rate, Atr M= Atrazine at manufacturer's rate, Atr H= Atrazine at higher rate, B1= sole *Tithonia diversifolia* biochar, B2= *Tithonia diversifolia* + Bonemeal biochar, SOCL= Soil organic carbon level, AC= Absolute control, HOC= High organic carbon soil, LOC= Low organic carbon soil, LSD= least significant difference mean at 5%.

Effects of different atrazine rates in soils with contrasting organic carbon content on leachate and soil Electrical conductivity EC

The effects of different atrazine rates and organic carbon levels on leachate and soil EC are presented in Tables 4. Leachate EC was significantly influenced by atrazine rate and soil organic carbon level, while their interaction was not significant. Soil EC, on the other hand, was significantly affected by atrazine rate, SOC level and their interaction. Leachate EC values ranged from 892 µS cm^{-1} (in Atr L) to 1298 µS cm^{-1} (in Atr L + B1) in LOC while 1029 µS cm^{-1} (in Atr H) to 1829 µS cm^{-1} (in Atr L + B1) was observed in HOC. Soil EC values ranged from 77.0 µS cm^{-1} (Atr M + B1, LOC) to 366.3 µS cm^{-1} (Atr M + B1, HOC), Atrazine application alone increased ionic concentrations in both leachate and soil EC compared with the absolute control (AC). For leachate EC, Atr L, Atr M, and Atr H recorded 1025, 1050, and 1123 µS cm^{-1} respectively, representing increases of 54–69% above AC (664 µS cm^{-1}). Soil EC followed a similar trend, with Atr H (274 µS cm^{-1}) increasing by 12% over AC (245 µS cm^{-1}), while Atr L and Atr M recorded slight reductions values (216–239 µS cm^{-1}). Biochar treatments further altered EC dynamics, and the direction of change depended on SOC level. In HOC soils, biochar sharply increased leachate EC, with Atr L + B1 recording the highest value (1829 µS cm^{-1}), a 175% increase compared with AC. Sole biochar treatments also raised leachate EC, with B1 and B2 increasing values by 104% and 77% compared with AC, respectively.

Soil EC, however, responded differently to biochar additions. In HOC soils, Atr M + B1 produced the highest soil EC (366.3 µS cm^{-1}), 8% higher than Atr M. By contrast, biochar in LOC soils tended to lower soil EC values (77–235 µS cm^{-1}), sometimes below the AC. Sole biochar treatments (B1 = 135 µS cm^{-1}; B2 = 133 µS cm^{-1}) reduced soil EC by 45–46% compared with AC.

These findings indicate that atrazine generally enhanced ionic mobility in leachates while moderately increasing soil ionic concentration. This pattern is consistent with Niemeyer *et al* (2023), who observed higher ionic conductivity in herbicide-impacted soils lacking strong retention capacity, but contrasts with Omara *et al* (2023), who found that biochar addition did not significantly increase soil electrical conductivity, implying ion stabilization under their conditions. The discrepancy may stem from the rapid decomposition of fresh Tithonia residues in this study, which released soluble ions faster than biochar surfaces could immobilize them. The contrasting responses between high-organic-carbon (HOC) and low-organic-carbon (LOC) soils align with the observation by Boostani *et al* (2023), who reported significant increases in soil EC following biochar additions under various treatments.

Table 4: Effects of different atrazine rate and organic carbon levels on leachate and soil Electrical conductivity EC

	Leachate EC (µScm^{-1})			Soil EC (µScm^{-1})		
	Soil organic carbon level			Soil organic carbon level		
Atrazine Rates	HOC	LOC	Mean	HOC	LOC	Mean
Atr L	1158	892	1025	291.0	141.00	216.00
Atr L + B1	1829	1298	1564	195.0	111.70	153.30
Atr L + B2	1425	1163	1294	312.3	95.70	204.00
Atr M	1123	978	1050	335.7	143.00	239.30
Atr M + B1 Atr	1444	1197	1320	366.3	77.00	221.70
M + B2 Atr H	1641	1173	1407	256.3	123.00	189.70
Atr H + B1 Atr H	1029	1216	1123	321.0	227.00	274.00
+ B2 Mean	1369	1224	1296	196.3	213.30	204.00
Atr (LSD) OCL	1624	1055	1339	217.67	235.67	226.70
(LSD)	1405	133		276.9	151.90	
Atr x OCL (LSD)	**			***		
	***			***		
Check AC B1 B2	NS			***		
	739	589	664	306.67	183.67	245.17
	1780	931	1356	169.67	100.67	135.17

Atr= Atrazine, Atr L= Atrazine at lower rate, Atr M= Atrazine at manufacturer's rate, Atr H= Atrazine at higher rate, B1= sole *Tithonia diversifolia* biochar, B2= *Tithonia diversifolia* + Bonemeal biochar, SOCL= Soil organic carbon level, AC= Absolute control, HOC= High organic carbon soil, LOC= Low organic carbon soil, LSD= least significant difference mean at 5%.

Effects of different atrazine rate and organic carbon levels on Leachate NO_3^--N and Po_4^{3-}

The effects of different atrazine rates and organic carbon levels on leachate nitrate (NO_3^--N) and phosphate (PO_4^{3-}) concentrations are presented in Table 5. Both NO_3^--N and PO_4^{3-} were significantly affected by atrazine rate, soil organic carbon level, and their interaction. Nitrate concentrations in leachate ranged from 6.37 mg L^{-1} (in Atr L + B2, LOC) to 9.84 mg L^{-1} (in Atr M + B2, HOC), while leachate phosphate content were generally much lower, ranging from 0.00 mg L^{-1} (several LOC treatments) to 0.35 mg L^{-1} (in Atr L + B2, HOC). Atrazine alone increased nitrate leaching compared with the absolute control (AC, 7.50 mg L⁻¹) with increasing atrazine rate . For example, nitrate concentration of leachate from Atr L, Atr M and Atr H were 8.50, 9.10 and 9.28 mg L⁻¹ respectively, representing increases of 13–24% higher nitrate content in leachate from AC. Phosphate leaching under atrazine-only treatments remained relatively low (0.04–0.26 mg L⁻¹) but still exceeded AC (0.126 mg L⁻¹) in some cases, showing increases of up to 40%. In HOC soils, Atr M + B2 recorded the highest nitrate concentration (9.84 mg L⁻¹), a 4% increase compared with Atr M. In LOC soils, nitrate values were more variable, with Atr L + B2 showing a reduction (6.37 mg L⁻¹, 15% below AC), while Atr M + B2 increased nitrate leaching to 9.18 mg L⁻¹, 4% above Atr M.

Phosphate concentrations in leachate were generally low, ranging from 0.00 mg L⁻¹ (in several LOC treatments) to 0.35 mg L⁻¹ (in Atr L + B2, HOC). Atrazine application alone resulted in phosphate losses compared with the absolute control (AC = 0.126 mg L⁻¹). Specifically, Atr L, Atr M, and Atr H recorded phosphate concentrations of 0.09, 0.04, and 0.26 mg L⁻¹, representing a 28.6% decrease, 68.3% decrease, and 106% increase, respectively, relative to the AC. The addition of biochar modified these trends differently across soils. In HOC soils, Atr L + B1 completely suppressed phosphate leaching (0.00 mg L⁻¹, a 100% reduction compared with Atr L), while Atr L + B2 markedly increased losses to 0.35 mg L⁻¹, a 289% rise relative to Atr L. Similarly, Atr M + B1 and Atr M + B2 recorded 0.20 mg L⁻¹ and 0.10 mg L⁻¹, representing 400% and 150% increases compared with Atr M, respectively. For Atr H treatments, the addition of biochar reduced phosphate leaching to 0.03 mg L⁻¹ (Atr H + B1) and 0.06 mg L⁻¹ (Atr H + B2), corresponding to 88.5% and 77% decreases compared with Atr H (0.26 mg L⁻¹). Sole biochar checks (B1 and B2) exhibited extremely low phosphate concentrations (0.002–0.003 mg L⁻¹), about 98% lower than the control, confirming biochar's strong phosphate-retentive capacity, particularly in the absence of herbicide application.

Table 5. Effects of different atrazine rate and organic carbon levels on Leachate NO_3^--N and Po_4^{3-}

	NO_3- N leached (mgl⁻¹)			PO_4 leached (mgl⁻¹)		
	Soil organic carbon level			Soil organic carbon level		
Atrazine Rates	HOC	LOC	Mean	HOC	LOC	Mean
Atr L	9.32	7.69	8.50	0.09	0.00	0.04
Atr L + B1	9.54	9.53	9.53	0.00	0.00	0.00
Atr L + B2	9.80	6.37	8.08	0.35	0.00	0.18
Atr M	9.42	8.78	9.10	0.04	0.20	0.12
Atr M + B1	9.65	8.82	9.23	0.20	0.00	0.10
Atr M + B2	9.84	9.18	9.51	0.10	0.00	0.05
Atr H	8.89	9.68	9.28	0.26	0.02	0.14
Atr H + B1	9.65	8.08	8.86	0.03	0.00	0.02
Atr H + B2	9.81	8.20	9.01	0.06	0.00	0.03
Mean	9.55	8.48		0.13	0.02	
Atr (LSD)	***			***		
OCL (LSD)	***			***		
Atr x OCL (LSD)	***			***		
Checks AC						
B1	8.25	6.75	7.50	0.252	0.00	0.126
B2	0.45	0.45	0.45	0.003	0.002	0.002
	0.71	0.45	0.58	0.003	0.003	0.003

Atr= Atrazine, Atr L= Atrazine at lower rate, Atr M= Atrazine at manufacturer's rate, Atr H= Atrazine at higher rate, B1= sole *Tithonia diversifolia* biochar, B2= *Tithonia diversifolia* + Bonemeal biochar, SOCL= Soil organic carbon level, AC= Absolute control, HOC= High organic carbon soil, LOC= Low organic carbon soil, LSD= least significant difference mean at 5%.

Effects of different atrazine rate and organic carbon levels on soil organic carbon and available phosphorus.

The effects of different atrazine rates and organic carbon levels on soil organic carbon (SOC) is presented in Fig 2. Soil organic carbon was significantly affected by atrazine rate, soil organic carbon level, and their interaction. The SOC values ranged from 0.74% (in Atr L, LOC) to 3.32% (in Atr H + B1, HOC). Sole atrazine use significantly reduced SOC by 6% and 4% in HOC(by Atr M) and LOC (by Atr L) respectively. Pre-treated sole soils with biochar consistently increased SOC in both soil (except in Atr M + B1). the B1 was superior to B2 in enhancing SOC at all atrazine rate except at Atr M in both soils. In HOC B1 increase SOC by 6% and 23 % at Atr L and Atr H respectively and by 82 % and 102 % respectively in LOC. The B2 pre-treatment however responsible for higher SOC enhancement in HOC and LOC soil at manufacturers application rate with 17 % and 25 % respectively relative to sole Atr M. similar higher organic carbon content AC were observed from soils treated with sole biochar regardless the type.

The effects of different atrazine rates and organic carbon levels on soil organic carbon (SOC) is presented in Fig 3. Available P was significantly affected by atrazine rate, soil organic carbon (OC) level , and their interaction. The available P values ranged from 9.66 mg kg⁻¹ (in Atr H, LOC) to 105.25 mg kg⁻¹ (in Atr L + B2, LOC). Sole atrazine use generally reduced available phosphorus in both soils, with decreases of 13% and 23% observed in HOC (by Atr M) and LOC (by Atr H) respectively, relative to the control. Pre-treated soils with biochar consistently enhanced available P across all treatments, with the magnitude of increase varying by biochar type and soil organic carbon level. The B2 biochar was superior to B1 in enhancing available P at nearly all atrazine rates, particularly in LOC soils. In HOC soils, B1 increased available P by 24% and 46% at Atr L and Atr H, respectively, compared with the corresponding sole atrazine treatments. In LOC soils, however, the increase was far greater, B1 raised available P by 35% and 42% at Atr L and Atr H, respectively. The B2 pre-treatment produced the highest increases in available P at the manufacturer's rate (Atr M) in both soils, elevating P by 28% in HOC and 91% in LOC relative to sole Atr M. Notably, Atr L + B2 in LOC soil exhibited the greatest overall enhancement, with available P rising to 105.25 mg kg^{-1}, nearly eight times higher than the control (12.53 mg kg^{-1}). Similar improvements in available P were observed in soils treated with sole biochar, regardless of type, confirming the strong P-releasing and retention capacity of biochar, especially when enriched with mineral additives such as bone meal.

These findings are consistent with Lehmann *et al* (2011), who reported that biochar improves SOC through stable carbon inputs and enhances nutrient retention. They also agree with Zheng *et al* (2013), who observed improved soil P status with biochar application under herbicide stress. Joseph *et al* (2021) similarly highlighted that biochar can release additional nutrients when enriched with mineral additives such as bone meal, explaining the exceptionally high available P values observed here. Conversely, the decline in SOC and P under atrazine-only treatments aligns with Tejada *et al* (2011), who reported that herbicide residues degrade soil organic matter quality and nutrient availability.

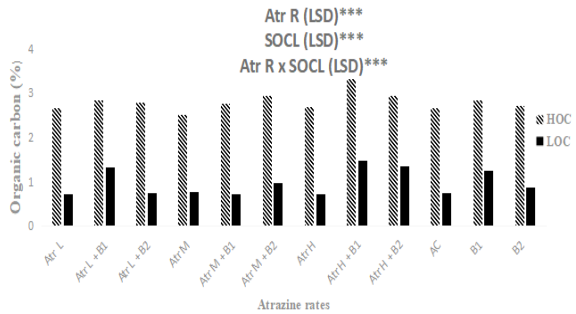


Fig2: Effects of different atrazine rate and organic carbon levels on soil organic carbon.
Atr= Atrazine, Atr R= Atrazine rate, Atr L= Atrazine at lower rate, Atr M= Atrazine at manufacturer's rate, Atr H= Atrazine at higher rate, B1= sole *Tithonia diversifolia,* B2= *Tithonia diversifolia* + Bonemeal, SOCL= Soil organic carbon level, AC= Absolute control, HOC= High organic carbon soil, LOC= Low organic carbon soil, LSD= least significant mean at 5%.

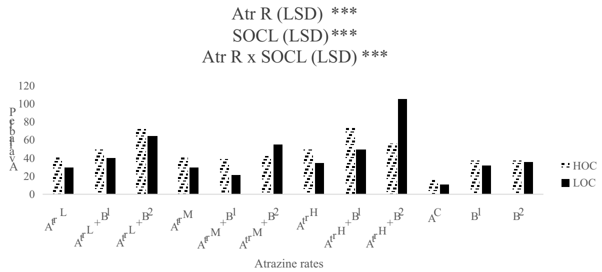


Fig 3. Effects of different atrazine rate and organic carbon levels on soil available P.
Atr= Atrazine, Atr R= Atrazine rate, Atr L= Atrazine at lower rate, Atr M= Atrazine at manufacturer's rate, Atr H= Atrazine at higher rate, B1= sole *Tithonia diversifolia,* B2= *Tithonia diversifolia* + Bonemeal, SOCL= Soil organic carbon level, AC= Absolute control, HOC= High organic carbon soil, LOC= Low organic carbon soil, LSD= least significant mean at 5%.

Conclusion

This study highlights that atrazine application alone reduced soil organic carbon by 5–9% (from a baseline of 1.72%) and available phosphorus by 15 – 40% (from 12.53 mg kg^{-1}), while increasing leachate TDS by 55 – 71% (333 – 569 mg L^{-1}), EC by 54 – 69% (664 – 1123 µS cm^{-1}), nitrate leaching by 13–24% (up to 9.28 mg L^{-1}), and phosphate losses by up to 40%. Biochar pretreatment markedly improved soil fertility, raising SOC by up to 93% (to 3.32%) and available P by 800% (to 105.25 mg kg^{-1}), but also amplified leachate solute loads in high-carbon soils, increasing TDS and EC by up to 177% and 175%, respectively. Sole biochar treatments, however, reduced nitrate and phosphate leaching by 94% and 98% while moderately enhancing SOC and available P. Overall, atrazine use poses risks of soil carbon and phosphorus depletion and increased nutrient leaching, but biochar pretreatment offers a sustainable strategy to mitigate these impacts if carefully managed to balance fertility gains with environmental safety.

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