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Effects of herbicides application on soil physicochemical properties

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Abstract

Twelve-week field experiment was conducted at Irewumi community, in Ilorin west local government area of Kwara state, to investigate the influence of S-metolachlor and Nicosulfuron herbicides on soil physicochemical properties. The experiment was a complete randomized block design with six treatments and four replicates. The treatment details include T_0 = pre-treatment; T_1 = 3 L/ha of S-metolachlor; T_2= 6 L/ha of S-metolachlor; T_3 = 1.5 L/ha of Nicosulfuron; T_4= 3 L/ha of Nicosulfuron and T_5 = weedy check. Physico-chemical properties, such as soil temperature, moisture content, pH, electrical conductivity, organic carbon, calcium, magnesium, potassium, sodium, exchangeable acidity, Nitrogen and soil organic matter were evaluated during the study. Both herbicides with the aforementioned active ingredient applied at a rate, which was twice the recommended rate significantly reduced soil organic carbon, calcium, magnesium, potassium, sodium and exchangeable acidity, although the decrease in soil temperature, and moisture and electrical conductivity were found to be statistically insignificant. It is worthy of note that soil treated with recommended application rate significantly increased all the soil physicochemical properties evaluated in this study. Therefore, the end users of pre-emergent and post-emergent herbicides containing S-metolachlor and Nicosulfuron, should adhere strictly to the recommended application rate to minimize the detrimental impact on soil physicochemical properties.

Key words: Nisosulfuron, S-metolachlor, soil, herbicides, weeds, physicochemical properties

Introduction

Sustainable agriculture, to a large extent, relies on the use of herbicide for optimal production, as they have contributed tremendously to both food and cash crop production all over the world, due to their economical and effective method of controlling weeds in both agricultural and uncultivated land (Gomez et al., 2008). The Nigerian market space have been flooded with all kinds of herbicides meant to control different kinds of weeds at different stages of their growth (Rose et al., 2016). However, the indiscriminate use of these agrochemicals, as well as their accumulative effect due to prolonged use, have contributed to environmental challenges on account of their toxicity ranging from destruction of the natural soil microflora, decline in organic matter content, which plays a vital role in soil fertility and productivity (Trimurtulu et al., 2015), soil and water pollution, which also play a vital role in bioaccumulation of heavy metals in target crop plants rooted in a polluted soil.

The fate of herbicides, like that of all organic molecules released into the environment, is determined by their physicochemical properties. (Pierzynski et al., 2005). Herbicide solubility is important for predicting behavior in water and mobility in soil. The water solubility of herbicides is a function of temperature, pH, and ionic strength, and is affected by the presence of other organic matter, such as dissolved organic matter (Pierzynski et al., 2005). A herbicide's ability to adsorb to soils and sediments and its tendency to desorb, are the most important factors affecting soil and water contamination (Alemayehu & Sheleme, 2013). Adsorption depends on both molecular and physicochemical properties of the soil (Andreu & Pico, 2004). There are colloidal particles, such as organic matter and clay on the soil surface that cause adsorption. Organics matter have the greatest adsorption capacity due to their chemical affinity with herbicide molecules. It has been reported that applying herbicides to soils has a significant impact on the characteristics of the soil. Soil parameters, such as soil texture, organic matter level, cation exchange capacity and pH, can influence the availability and effectiveness of herbicides applied to the soil (Alemayehu & Sheleme, 2013). The organic matter composition, however, has the greatest impact. Herbicide adsorption increases with the amount of organic matter present. With selective herbicides and other positively charged herbicides, the soil's ability to store positively charged ions in an exchangeable state is crucial (Andreu & Pico, 2004). For ionizable herbicides, such as atrazine, S-metolachlor, adsorption rises with increased soil acidity. According to several studies, the active components of these herbicides have the ability to negatively impact soil processes and functioning (Araújo et al., 2003; George et al., 2009). After an herbicide has been administered, its active components may remain in the soil matrix for a while (George et al., 2009). It has also been reported that application of herbicides to soils has a significant impact on soil characteristics, such as soil texture, organic matter content, pH, etc. (Andreu & Pico, 2004). Some soil microorganisms have been demonstrated to be adversely affected by herbicides like S-metolachlor, where growth is greatly inhibited by exposure to high concentrations of herbicides (George et al., 2009). The ability of herbicides containing these active ingredients to change soil acidity is one potential drawback Wolmarans & Swart, 2014). The herbicide's toxicity may be strong and long-lasting enough to increase soil acidity, reduce soil fertility, or even weaken native plant species metabolism, making them more vulnerable to pathogen attack. Herbicides have reportedly been shown to promote various soil properties as opposed to having the inhibitory impact indicated above. According to Reddy et al. (2003), the herbicide treatment (which included paraquat, Nicosulfuron, and metolachlor), greatly improved the amount of accessible nitrogen in the soil. In an attempt to address the aforementioned challenges, Nicosulfuron and S-metolachlor have been incorporated as active ingredients of selective pre-emergent and post-emergent herbicides, respectively, which confers the advantage of low toxicity and high weed control efficiency on the herbicides however, available information on their effect on soil physicochemical properties is grossly inadequate, it is therefore important to study the effect of selected herbicide with Nicosulfuron and S-metolachlor on soil physicochemical properties, for proper management and longtime productivity.

Materials and methods

Experimental site

The experiment was conducted in 2021 growing season, at Irewumi community, located at Ilorin west local government area, Kwara state, located on latitude 8^0 31.36.5' N and 8^0 52680.3' N, and longitude 4^0 31'40.6'' E and 4^0 52.7930' E. The climate of research area is characterized by an average monthly rainfall of 10.34- 38.57, annual temperature range of 22-33° C and average relative humidity of 78.93-85.88%.

Soil sampling and determination of the physicochemical parameters

Soil samples were collected from ten (10) different locations at the experimental site prior to the herbicide application. The technique used to collect 10 cores of soil from these locations was achieved by using random sampling approach, within 10 quadrats, each of 1 m^2 at 0 -30 cm depths, using a soil auger after clearing the field. Subsequently, plot by plot, soil samples were taken fortnightly for 12 weeks after the application of herbicides. The soil samples were air dried, crushed and passed through a 2 mm sieve for laboratory analysis. The following analyses were carried out on each soil sample: Soil temperature was evaluated according to (Globe, 2014) by inserting the thermometer probe in to the pilot hole of the soil to read the temperature. The soil moisture was determined using the methods described by Ukpong et al. (2013). The soil pH was determined in distilled water using a glass electrode pH meter of 1:1 soil-water suspension ratio, as described by Emmanuel et al, (2018). Electrical conductivity of the soil was determined using a conductivity meter as described by Haluschak (2006). The organic carbon of the soils was determined by colorimetric method, using dichromate digestion procedure, using Walkley & Black (1934) as adopted by Azam & Sajjad (2005). Exchangeable bases (Ca) and magnesium (Mg) were determined by Atomic Absorption spectrophotometry as outlined by Anderson & Ingram (1993), while sodium (Na) and potassium (K) were determined by Flame Photometry as described by Anderson & Ingram (1993). Exchangeable acidity was determined by titrimetric method according to the method described by International Institute of Tropical Agriculture (IITA) (1979).

Herbicides

The herbicides used in this study were obtained from an agricultural store in Ilorin. The herbicides that were used are Strim with active ingredient S-metolachlor trademark of UPL Limited, and Striker with active ingredient Nicosulfuron a product of Saro Agrosciences.

Experimental design and treatment details

The experiment was laid out in a Randomized complete block design (RCBD) with six treatments and four replicates. The experimental site has a dimension of 23.23 m by 15 m comprising of four blocks, each containing six (6) beds of 3 m by 3 m with 1 m alley between blocks and beds. There were six treatments, T_0 = pre- treatmet, T_1 = 3 L/ha of S-metolachlor, T_2 = 6 L/ha of S-metolachlor, T_3 = 1.5 L/ha of Nicosulfuron, T_4 = 3 L/ha of Nicosulfuron, T_5 = weedy check (unweeded). Data were collected on the above-mentioned physical and chemical properties and statistical tools employed to analyze them. Data collected were subjected to analysis of variance (ANOVA) using Statistical Package of Social Science (SPSS) and means were separated using Duncan's Multiple Range Test (DMRT) at 5% level of probability.

Results and discussion

Soil temperature had no significant ($P \leq 0.05$) effect amongst all the pre-treatment and till 6

Table 1. Effects of herbicides application on soil temperature (^{0}C)

Treat-ments	Weeks After Treatment (WAT)						
	Pre-Treat-ments	2	4	6	8	10	12
T_o	20.21±1.04^a	20.30±0.53^a	20.64±0.39^a	20.43±0.57^a	20.80±0.49^a	21.93±0.60^a	21.96±1.07^a
T_1	20.73±0.43^a	21.20±1.10^a	20.45±0.52^a	20.30±0.86^a	20.49±0.31^a	20.47±0.32^{ab}	20.60±0.20^a
T_2	21.30±0.93^a	21.60±1.04^a	20.73±0.53^a	21.57±0.50^a	20.87±0.29^a	20.67±0.66ab	20.87±0.94^a
T_3	21.07±0.71^a	20.77±0.42^a	20.45±0.65^a	20.38±0.68^a	20.59±0.53^a	20.77±0.46^{ab}	21.47±0.40^a
T_4	21.17±0.95^a	20.89±0.32^a	20.96±0.13^a	20.47±0.43^a	20.50±0.44^a	20.53±0.63^{ab}	21.60±0.44^a
T_5	20.27±0.98^a	21.77±0.31^a	20.72±0.39^a	18.47±0.50^a	18.97±0.50^b	19.67±0.17^b	19.93±0.31^a

Means with the same superscript across the column are not significantly different at P ≤ 0.05 T_0 = control (weed free); T_1= 3 L/ha of S-metolachlor; T_2= 6 L/ha of S-metolachlor; T_3 = 1.5 L/ha of Nicosulfuron; T_4= 3 L/ha of Nicosulfuron; T_5= weedy check

Table 2. Effects of herbicides application on soil moisture (%)

Treatments	Weeks After Treatment (WAT)						
	Pre-Treat-ments	2	4	6	8	10	12
T_o	1.06±0.01^a	1.17±0.01^c	1.50±0.03^c	1.52±0.01^b	1.56±0.02^c	1.56±0.08^c	1.63±0.09^a
T_1	1.06±0.01^a	1.19±0.01^c	1.27±0.03^d	1.54±0.02^b	1.59±0.01^{bc}	1.64±0.01^{bc}	1.67±0.03^a
T_2	1.04±0.1^a	1.15±0.03^c	1.23±0.02^d	1.50±0.02^b	1.56±0.03^c	1.56±0.03^c	1.62±0.08^a
T_3	1.05±0.19^a	1.36±0.01^b	1.60±0.01^b	1.70±0.01^a	1.72±0.01^a	1.74±0.03^{ab}	1.77±0.08^a
T_4	1.05±0.03^a	1.21±0.03^c	1.56±0.03^{bc}	1.66±0.08^a	1.70±0.09^{ab}	1.73±0.02^{ab}	1.69±0.06^a
T_5	1.05±0.01^a	1.50±0.01^a	1.69±0.04^a	1.70±0.02^a	1.79±0.01^a	1.79±0.01^a	1.79±0.01^a

Means with the same superscript across the column are not significantly different at P ≤ 0.05 T_0 = control (weed free); T_1 = 3 L/ha of S-metolachlor; T_2 = 6 L/ha of S-metolachlor; T_3 = 1.5 L/ha of Nicosulfuron; T_4 = 3 L/ ha of Nicosulfuron; T_5 = weedy check

Table 3. Effects of herbicides application on soil pH

Treatments	Weeks After Treatment (WAT)						
	Pre-Treat-ments	2	4	6	8	10	12
T_o	7.84±0.01^a	7.86±0.00^a	7.88±0.01^a	7.50±0.10^{ab}	7.60±0.03^a	7.70±0.37^a	7.80±0.03^a
T_1	7.80±0.01^a	7.30±0.01^b	7.23±0.01^b	7.22±0.01^b	7.07±0.15^a	7.13±0.05^{ab}	6.20±0.10^c
T_2	7.60±0.20^a	7.10±0.03^c	7.26±0.11^b	7.18±0.17^{bc}	6.80±0.05^{bc}	6.53±0.10^{bc}	6.10±0.13^c
T_3	7.60±0.20^a	7.48±0.03^b	7.40±0.10^b	7.30±0.10^{ab}	6.73±0.17^{bc}	7.30±0.27^a	7.30±0.07^b
T_4	7.60±0.20^a	7.50±0;07^b	7.36±0.17^b	6.85±0.23^c	6.47±0.27^c	6.30±0.17^c	6.00±0.07^c
T_5	7.80±0.03^a	7.83±0.02^a	7.82±0.07^a	7.66±0.07^a	7.70±0.03^a	7.75±0.05^a	7.77±0.07^a

Means with the same superscript across the column are not significantly different at P ≤ 0.05 T_0 = control (weed free); T_1 = 3 L/ha of S-metolachlor; T_2 = 6 L/ha of S-metolachlor; T_3 = 1.5 L/ha of Nicosulfuron; T_4 = 3 L/ ha of Nicosulfuron; T_5 = weedy check weeks after herbicides application (table 1). Thereafter, there were variation in the soil temperature amongst the treatment between 8-12 weeks after herbicides application. However, the variations were found to be statistically the same ($P \leq 0.05$). Statistically the same soil temperature in the variation among all the treatment, could be adduced to microclimatic condition of the environment, where the planting was conducted. The result is in accordance with the work of Onwuka & Mang (2018), who reported a statistically similar variation in daily soil temperature, which was described as a function of the radiant energy from the sun, which strikes the soil surface.

Soil moisture content was lowest before treatment with herbicide, when compared to all other sampling period, this increased gradually as the number of weeks after application increased until 10 weeks beyond, which no variation was recorded throughout the sampling period (table 2). It should be noted that all herbicides application significantly increased the soil moisture content of the soil. Water acts as solvent, which facilitate the diffusion of herbicides and it is also an essential component of the soil microbial flora. Significant reduction in soil moisture content at 0 week before herbicide could be adduced to increased soil temperature, which decrease water viscosity, thus allowing more water to percolate through the soil profile (Broadbent, 2015). This result is in agreement with the work of Rengasamy & Churchman (1999), who reported that reduced shade combined with increased soil temperature, also result in higher evaporation rates, which in turn restrict the downward movement of water into the soil. Significant increase in the soil moisture content of the herbicide treated soil could be mulch formation on soil surface by falling leaves following the death of the weed after application of the herbicides (Rajcan & Swanton, 2001; Rengasamy & Churchman, 1999).

There was no significant effect on the soil pH prior to herbicide application (table 3). Beyond that, a significantly higher soil pH was recorded on weed free and weedy check, when compared to all other treatments throughout the sampling period. Herbicide treated plot had a significantly lower pH content. It should also be noted that soil treated with 6 L/ha and 3 L/ha for pre and post emergence herbicides, respectively, had significant lowest pH content at 12 weeks after herbicides application, when compared to all other treatment plots. Significant highest soil pH recorded in the weedy check and control plot throughout the sampling period could be adduced to the relative alkalinity of the soil as a result of enhanced production of soil microorganism since herbicide were not applied (Neina, 2019). However, significant decrease in the pH content of soil treated with twice the recommended rate of herbicide application could be as a result of decreased soil microorganisms on account of toxicity created by the relative soil acidity (Brady & Weil, 2002).

Herbicides application had no significant effects on electrical conductivity of the soil. Electrical conductivity of all the soil sample remained stable before herbicide application and till 8 weeks after treatment except the weedy check plot that showed a decrease at 10-12 weeks after treatment, when compared to the control plot (table 4). Soil electrical conductivity is a measure of the soil's ability to transmit electrical currents. It serves as an indirect indicator of soil salinity in the soil. Significance reduction in the electrical conductivity of the weedy check plot at 10-12 weeks after herbicide application might be due to low temperature levels during the sampling period since electrical conductivity is temperature depended (Visconti & de Paz, 2016).

Soil, treated with recommended rate of herbicides significantly ($P \leq 0.05$) increase the organic carbon content of the soil at the end of the sampling period (table 5). Soil, treated with twice the recommended rate of pre and post emergence herbicide significantly decreased the organic carbon content of the soil at 10-12 weeks after herbicides application, when compared to the control plot. However, both the weed free and the weedy check plot increased significantly ($P \leq 0.05$) before herbicides application and at 8 weeks after treatment, but with a significant decrease in the weedy check plot at 8-12 weeks (table 5). Significance increase in the soil organic carbon content of soil, treated with recommended rate of applications, could be as a result of herbicides degradation by the microorganism, which has been utilize as a carbon source to support their growth (Ayansina & Oso, 2006). Significant decrease in the carbon content of the soil, treated with 6 L/ha of S-metolachlor and 3 L/ha of Nicosulfuron, could be adduced to lysis of microbial cell following the adsorption of the chemicals by the soil microorganisms due to the toxicity, created by the herbicide at such high concentration (Jayamadhuri & Rangaswamy, 2005). In addition, significant decrease recorded in the soil carbon content of the weedy check plot might be due to lower root biomass of the crop plant, produced in the weedy check plot lower than the control and all treated plot (Brar & Walia, 2008).

Herbicides applied at twice the recommended rate significantly ($P \leq 0.05$) decreased the exchangeable bases, such as Na^{+}, Ca^{2+}, K^{+} and Mg^{2+}, when compared to all the treatments, this was followed by soil samples, treated with the recommended rate with the highest exchangeable cation recorded in the control and weedy (table 6, 7, 8 and 9). Significant decrease in the exchangeable bases of the soil might be as a result of leaching effect of the herbicide to the soil, which cause distortion of the soil microbes and hence affect exchangeable cations. Lemma (2013), also reported that cation exchange capacity, such as Magnesium, Sodium, Calcium and potassium has been established decrease with soil organic carbon. In addition, the use of pre and post emergrnt herbicides significantly ($P \leq 0.05$) increased the magnesium content of the soil. This may be due to the herbicide's degradation processes in the soil, which produced breakdown products containing magnesium and helped in the release of magnesium from soil minerals, boosting the soil's magnesium concentration (Blasioli et al., 2011).

There were no significant effects on exchangeable acidity of the soil prior to herbicides application (table 10). The weedy check and weed free soil significantly ($P \leq 0.05$) decreased the exchangeable acidity of the soil at 12 weeks after treatment, when compared to all other herbicide treated soil. However, soil treated with 6 L/ha of S-metolachlor significantly increased the exchangeable acidity of the soil at 2-12 weeks. This was followed by 3 L/ha of Nicosulfuron, while the control and the weedy check plot recorded the lowest exchangeable acidity. Significant increase in the exchangeable acidity of soil treated with twice the recommended rate of application could be as a result of decrease in the organic matter content of the soil on an account of low soil pH (Ataikiru et al., 2019). However, decrease in the soil exchangeable acidity of the herbicide free soil could be as a result of the increase alkalinity of the soil on an account of increase in soil pH (Ayansina & Oso 2006).

Soil samples, treated with S-metolachlor significantly decreased nitrogen content irrespective of their concentration, when compared to the pretreatment. This was followed by the weedy check, while samples, treated with nicosulfuron, as well as the control plot recoded the highest Nitrogen content (table 11). Significant decrease in Nitrogen content of soil, treated with S-metolachlor at the end of the sampling period may be due to the high sensitivity of nitrogen fixing bacteria to the herbicide (Zafar et al., 2014). This result is supported by Zabaloy & Gómez (2008), who reported that herbicides application suppresses N-fixing bacteria from replenishing natural fertilizer in soil resulting in death of microorganism and lower crop yield. It has been reported by Effiong et al. (2009) that organic matter is the main source of total nitrogen and base saturation and contributes slightly to exchangeable K and Na concentrations in the soils. Significant highest nitrogen content recorded in the control plot, and plot treated with 1.5 L/ha of Nicosulfuron at 12 weeks after treatment could be adduced to more nitrogen content uptake by the soil in maize plot (Brar & Walia, 2008).

Table 4. Effects of herbicides application on soil electrical conductivity (dsm^{-1})

Treatments	Weeks After Treatment (WAT)						
	Pre-Treatments	2	4	6	8	10	12
T_o	1.70±0.03^{a}	1.78±0.05^{a}	1.78±0.04^{a}	1.79±0.04^{a}	1.81±0.05^{a}	1.83±0.02^{a}	1.85±0.01^{a}
T_1	1.71±0.01^{a}	1.79±0.03^{a}	1.78±0.01^{a}	1.78±0.01^{a}	1.78±0.01^{a}	1.80±0.02^{ab}	1.76±0.01^{b}
T_2	1.70±0.04^{a}	1.78±0.03^{a}	1.76±0.05^{a}	1.78±0.04^{a}	1.80±0.02^{a}	1.76±0.02^{bc}	1.74±0.00^{b}
T_3	1.70±0.05^{a}	1.72±0.03^{a}	1.77±0.01^{a}	1.78±0.01^{a}	1.81±0.02^{a}	1.81±0.02^{ab}	1.84±0.01^{a}
T_4	1.69±0.04^{a}	1.76±0.01^{a}	1.77±0.01^{a}	1.77±0.03^{a}	1.81±0.01^{a}	1.81±0.01^{ab}	1.82±0.01a
T_5	1.70±0.04^{a}	1.80±0.01^{a}	1.78±0.01^{a}	1.70±0.04^{a}	1.72±0.01^{a}	1.71±0.01^{c}	1.69±0.02^{c}

Means with the same superscript across the column are not significantly different at $P \leq 0.05$ T_0 = control (weed free); T_1 = 3 L/ha of S-metolachlor; T_2 = 6 L/ha of S-metolachlor; T_3 = 1.5 L/ha of Nicosulfuron; T_4 = 3 L/ ha of Nicosulfuron; T_5 = weedy check

Table 5. Effects of herbicides application on soil Organic carbon (%)

Treatments	Weeks After Treatment (WAT)						
	Pre-Treatments	2	4	6	8	10	12
T_o	2.31±0.02^{a}	2.33±0.02^{a}	2.34±0.02^{a}	2.36±0.03^{ab}	2.40±0.03^{b}	2.46±0.01^{b}	2.43±0.01^{b}
T_1	2.31±0.02^{a}	2.10±0.02^{b}	2.33±0.02^{a}	2.40±0.01^{ab}	2.52±0.03^{a}	2.58±0.01^{a}	2.57±0.01^{a}
T_2	2.30±0.07^{a}	1.80±0.02^{c}	2.10±0.01^{b}	2.32±0.02^{bc}	2.40±0.01^{b}	2.27±0.02^{d}	2.00±0.01^{d}
T_3	2.29±0.03^{a}	2.36±0.01^{a}	2.36±0.02^{a}	2.31±0.03^{c}	2.52±0.05^{a}	2.57±0.03^{a}	2.56±0.02^{a}
T_4	2.29±0.03^{a}	2.38±0.03^{a}	2.32±0.01^{a}	2.23±0.01^{d}	2.38±0.03^{b}	2.36±0.02^{c}	2.10±0.05^{c}
T_5	2.30±0.02^{a}	2.37±0.01^{a}	2.34±0.02^{a}	2.36±0.01^{ab}	2.00±0.03^{c}	1.80±0.02^{e}	1.72±0.01^{e}

Means with the same superscript across the column are not significantly different at $P \leq 0.05$ T_0 = control (weed free); T_1 = 3 L/ha of S-metolachlor; T_2 = 6 L/ha of S-metolachlor; T_3 = 1.5 L/ha of Nicosulfuron; T_4 = 3 L/ ha of Nicosulfuron; T_5 = weedy check

Table 6. Effects of herbicides application on soil Sodium (cmol/kg)

Treatments	Weeks After Treatment (WAT)						
	Pre-Treatments	2	4	6	8	10	12
T_o	1.70±0.03^{a}	1.72±0.05^{a}	1.74±0.06^{ab}	1.74±0.05^{a}	1.75±0.01^{a}	1.76±0.02^{a}	1.78±0.05^{a}
T_1	1.73±0.01^{a}	1.75±0.01^{a}	1.78±0.06^{a}	1.63±0.03^{ab}	1.68±0.05^{ab}	1.66±0.02^{ab}	1.60±0.02^{bc}
T_2	1.70±0.13^{a}	1.72±0.09^{a}	1.65±0.06^{abc}	1.60±0.06^{ab}	1.60±0.06^{abc}	1.58±0.08^{b}	1.52±0.03^{cd}
T_3	1.76±0.08^{a}	1.78±0.09^{a}	1.58±0.08^{bc}	1.56±0.02^{b}	1.46±0.03^{c}	1.43±0.01^{c}	1.38±0.01^{de}
T_4	1.75±0.03^{a}	1.75±0.07^{a}	1.53±0.01^{c}	1.48±0.08^{b}	1.50±0.12^{bc}	1.36±0.05^{c}	1.32±0.10^{e}
T_5	1.66±0.02^{a}	1.70±0.02^{a}	1.75±0.05^{ab}	1.75±0.05^{a}	1.71±0.03^{a}	1.73±0.03^{a}	1.74±0.03^{ab}

Means with the same superscript across the column are not significantly different at $P \leq 0.05$ T_0 = control (weed free); T_1 = 3 L/ha of S-metolachlor; T_2 = 6 L/ha of S-metolachlor; T_3 = 1.5 L/ha of Nicosulfuron; T_4 = 3 L/ ha of Nicosulfuron; T_5 = weedy check

Table 7. Effects of herbicides application on soil Calcium (cmol/kg)

Treatments	Weeks After Treatment (WAT)						
	Pre-Treat-ments	2	4	6	8	10	12
T_o	4.50±0.03^{b}	4.57±0.01^{a}	4.70±0.02^{a}	4.75±0.02^{a}	4.79±0.01^{a}	4.83±0.01^{a}	4.87±0.01^{a}
T_1	4.56±0.01^{a}	4.30±0.07^{b}	4.19±0.06^{b}	3.80±0.10^{b}	3.20±0.14^{d}	3.00±0.09^{c}	2.80±0.17^{c}
T_2	4.55±0.02$_{ab}$	4.20±0.02$_{c}$	4.26±0.07$_{b}$	3.31±0.20$_{c}$	2.87±0.12^{e}	2.60±0.33^{c}	2.20±0.43$_{c}$
T_3	4.56±0.0-1^{a}	4.58±0.01^{a}	4.63±0.01^{a}	4.64±0.02^{a}	4.28±0.03^{b}	3.76±0.06^{b}	3.62±0.12^{b}
T_4	4.57±0.01^{a}	4.60±0.00^{a}	4.72±0.02^{a}	4.62±0.01^{a}	3.85±0.01^{c}	3.61±0.05^{b}	3.43±0.08^{b}
T_5	4.55±0.02^{ab}	4.60±0.00^{a}	4.65±0.01^{a}	4.65±0.01^{a}	4.69±0.01^{a}	4.74±0.01^{a}	4.82±0.01^{a}

Means with the same superscript across the column are not significantly different at $P \leq 0.05$ T_0 = control (weed free); T_1 = 3 L/ha of S-metolachlor; T_2 = 6 L/ha of S-metolachlor; T_3 = 1.5 L/ha of Nicosulfuron; T_4 = 3 L/ ha of Nicosulfu-ron; T_5 = weedy check

Table 8. Effects of herbicides application on soil Potassium (cmol/kg)

Treatments	Weeks After Treatment (WAT)						
	Pre-Treat-ments	2	4	6	8	10	12
T_o	2.61±0.66^{a}	2.26±0.07^{a}	2.28±0.03^{a}	2.28±0.01^{a}	2.90±0.02^{a}	2.93±0.02^{a}	2.90±0.08^{a}
T_1	2.32±0.03^{a}	2.08±0.01^{ab}	2.07±0.02^{c}	2.03±0.02^{ab}	2.03±0.09^{b}	1.82±0.12^{b}	1.65±0.15^{b}
T_2	2.21±0.02^{a}	1.97±0.08^{b}	2.06±0.02^{c}	1.97±0.18^{b}	1.76±0.16^{c}	1.73±0.11^{b}	1.48±0.08^{b}
T_3	2.31±0.10^{a}	2.18±0.03^{a}	2.13±0.02^{bc}	2.10±0.02^{ab}	2.10±0.02^{b}	1.61±0.03^{b}	1.64±0.03^{b}
T_4	2.25±0.07^{a}	2.21±0.07^{a}	2.15±0.08^{abc}	1.86±0.05^{b}	1.85±0.05^{bc}	1.58±0.13^{b}	1.52±0.08^{b}
T_5	2.00±0.10^{a}	2.25±0.08^{a}	2.25±0.05^{ab}	2.23±0.01^{a}	2.89±0.04^{a}	2.90±0.08^{a}	2.91±0.05^{a}

Means with the same superscript across the column are not significantly different at $P \leq 0.05$ T_0 = control (weed free); T_1 = 3 L/ha of S-metolachlor; T_2 = 6 L/ha of S-metolachlor; T_3 = 1.5 L/ha of Nicosulfuron; T_4 = 3 L/ ha of Nicosulfu-ron; T_5 = weedy check

Table 9. Effects of herbicides application on soil Magnesium (cmol/kg)

Treatments	Weeks After Treatment (WAT)						
	Pre-Treat-ments	2	4	6	8	10	12
T_o	1.32±0.14^{a}	2.23±0.06^{ab}	2.45±0.08^{a}	2.49±0.02^{a}	2.57±0.06^{a}	2.69±0.03^{a}	2.94±0.02^{a}
T_1	1.35±0.01^{a}	1.80±0.01^{d}	2.00±0.12^{b}	2.24±0.05^{a}	2.36±0.21^{a}	2.47±0.03^{a}	2.70±0.08^{a}
T2	1.30±0.05^{a}	1.38±0.01^{e}	1.38±0.03^{c}	1.41±0.05^{b}	1.47±0.04^{b}	1.43±0.06^{b}	1.38±0.03^{c}
T_3	1.32±0.05^{a}	2.18±0.05^{b}	2.39±0.23^{ab}	2.21±0.10^{a}	2.19±0.34^{a}	2.15±0.38^{a}	2.15±0.24^{b}
T_4	1.32±0.06^{a}	2.00±0.03^{c}	2.39±0.23^{ab}	2.18±0.30^{a}	2.29±0.32^{a}	2.20±0.35^{a}	2.19±0.24^{b}
T_5	1.32±0.06^{a}	2.30±0.02^{a}	2.36±0.08^{ab}	2.40±0.27^{a}	2.48±0.21^{a}	2.52±0.16^{a}	2.86±0.05^{a}

Means with the same superscript across the column are not significantly different at $P \leq 0.05$ T_0 = control (weed free); T_1 = 3 L/ha of S-metolachlor; T_2 = 6 L/ha of S-metolachlor; T_3 = 1.5 L/ha of Nicosulfuron; T_4 = 3 L/ ha of Nicosulfu-ron; T_5 = weedy check

Table 10. Effects of herbicides application on soil Exchangeable acidity (cmol/kg)

Treatments	Weeks After Treatment (WAT)						
	Pre-Treatments	2	4	6	8	10	12
T_o	1.72±0.02^{a}	1.71±0.03^{bc}	1.66±0.01^{bc}	1.66±0.03^{b}	1.67±0.01^{c}	1.71±0.02^{b}	1.71±0.01^{bc}
T_1	1.71±0.01^{ab}	1.74±0.03^{bc}	1.69±0.01^{b}	1.73±0.03^{b}	1.76±0.05^{b}	1.75±0.01^{b}	1.79±0.01^{ab}
T_2	1.71±0.02^{ab}	1.85±0.01^{a}	1.87±0.02^{a}	1.92±0.02^{a}	1.96±0.03^{a}	1.88±0.01^{a}	1.89±0.02^{a}
T_3	1.67±0.01^{b}	1.69±0.03^{bc}	1.66±0.01^{bc}	1.68±0.01^{b}	1.64±0.02^{c}	1.69±0.03^{bc}	1.69±0.01^{bc}
T_4	1.69±0.00^{ab}	1.78±0.03^{ab}	1.65±0.01^{c}	1.88±0.03^{a}	1.89±0.02^{a}	1.92±0.02^{a}	1.85±0.08^{a}
T_5	1.72±0.02^{a}	1.65±0.04^{c}	1.68±0.04^{bc}	1.68±0.04^{b}	1.65±0.01^{c}	1.64±0.01^{c}	1.66±0.03^{c}

Means with the same superscript across the column are not significantly different at $P \leq 0.05$ T_0 = control (weed free); T_1 = 3 L/ha of S-metolachlor; T_2 = 6 L/ha of S-metolachlor; T_3 = 1.5 L/ha of Nicosulfuron; T_4 = 3 L/ ha of Nicosulfuron; T_5 = weedy check

Table 11. Effects of herbicides application on Soil Nitrogen ($g.kg^{-1}$)

Treatments	Weeks After Treatment (WAT)						
	Pre-Treatments	2	4	6	8	10	12
T_o	2.44±0.06^{a}	2.32±0.01^{b}	2.44±0.08^{a}	2.46±1.00^{a}	2.75±1.03^{a}	2.80±0.22^{a}	2.80±0.08^{a}
T_1	2.43±0.05^{a}	2.21±0.03^{c}	2.19±0.01^{c}	2.19±0.01^{c}	2.22±0.01^{d}	2.22±0.05^{c}	2.23±0.01^{c}
T_2	2.39±0.00^{c}	2.10±0.01^{b}	2.16±0.03^{c}	2.19±0.01^{c}	2.15±0.01^{e}	2.19±0.01^{c}	2.06±0.01^{d}
T_3	2.40±0.00^{bc}	2.33±0.07^{ab}	2.39±0.01^{ab}	2.39±0.03^{b}	2.46±0.06^{b}	2.56±0.23^{ab}	2.58±0.06^{b}
T_4	2.40±0.00^{bc}	2.50±1.02^{a}	2.33±0.01^{b}	2.28±0.01^{c}	2.35±0.01^{c}	2.28±0.01^{bc}	2.23±0.01^{c}
T_5	2.42±0.03^{ab}	2.33±0.06^{ab}	2.41±0.06^{ab}	2.15±0.03^{d}	2.13±0.01^{e}	2.16±0.02^{c}	2.00±0.01^{d}

Means with the same superscript across the column are not significantly different at $P \leq 0.05$ T_0 = control (weed free); T_1 = 3 L/ha of S-metolachlor; T_2 = 6 L/ha of S-metolachlor; T_3 = 1.5 L/ha of Nicosulfuron; T_4 = 3 L/ ha of Nicosulfuron; T_5 = weedy check

Conclusion

The specific effects of S-metolachlor and Nicosulfuron on soil physicochemical properties can be influenced by various factors and may vary in different soil and environmental conditions. The present study has shown that the application of pre-emergent and post-emergent herbicides containing S-metolachlor and Nicosulfuron as active ingredient, respectively, at twice the recommended rate impact the soil negatively through decreased soil organic carbon, exchangeable bases, exchangeable acidity and soil pH. It is therefore advisable that farmers using herbicides with the aforementioned active ingredient should stick to the recommended rate to minimize the detrimental impact on soil physicochemical properties.

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