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Soil Fertility Improvement by Using *Crotalaria* Species Combined to Organic Amendment

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Abstract

In Burkina Faso, agricultural land degradation, including soil fertility decline, has prompted the implementation of agricultural innovations to address this challenge. Therefore, this study aimed to evaluate the contribution of four Papilionaceous ecotypes in enhancing the fertility of degraded soils. Experiments were conducted in Noumousso and Arbollé from July to December 2024, using a randomized split-plot design combining ecotypes and organic matter and/or Burkina Phosphate amendments. Amendments were applied in four treatments: T0 (control), T1 (Organic Matter), T2 (OM + Burkina Phosphate), and T3 (BP). Determined physico-chemical properties were: particle size distribution, pH, carbon (C), nitrogen (Nt), total Phosphorus (P_t), available P (P_Bray), potassium (Kt), exchangeable bases (EB), cation exchange capacity (CEC), and saturation rate (SR). The evaluated agronomic parameter was total biomass. Results revealed that the soils at both sites were characterized by acidic sandy-clay texture and low levels of C, N, P, K, EB, and CEC. Cultivating papilionaceous and applying organo-mineral amendments contributed to increased levels of C, available P, and Mg^{2+}, as well as improved SR. Acidity decreased at Arbollé, while showing a slight increase at Noumousso. Interaction between the two factors helped reduce acidity at both sites and significantly increased C, N, and available P contents. The organo-mineral amendment also enhanced biomass production across all ecotypes. At Noumousso, compared to T0, OM, OM + BP, and BP treatments resulted in biomass increases of 64.8%, 73.1%, and 38.6%, respectively. At Arbollé, the corresponding increases were 33.5%, 47%, and 23.4%. On both sites, OM + BP amendment had the greatest impact on improving biomass production, followed by organic amendment. These findings are of great importance to farmers for restoring the fertility of degraded soils. Therefore, the use of leguminous species in combination with organic matter enriched with Burkina Phosphate could be an alternative for improving the fertility of degraded soils.

Keywords

Agricultural Innovations, Burkina Phosphate, Herbaceous Papilionaceous, Organic Matter

1. Introduction

In Sub-Saharan Africa, particularly in the Sahel region, the degradation of arable land has intensified in recent decades under the combined influence of anthropogenic factors and climate change effects [1] [2]. This alarming situation was highlighted by the FAO [3], indicating that in arid and semi-arid areas, any zonal destruction of vegetative cover rapidly leads to the formation of a desert enclave. Schulz and Pomel [4] demonstrated that this situation could worsen when climatic conditions become unfavorable, hindering natural regeneration. Hence, there is an increasingly significant emergence of lands unsuitable for plant and animal production.

In Burkina Faso, similar to other countries in Sub-Saharan Africa, this phenomenon has led to significant declines in agricultural and livestock productions [5] [6]. In the agro-ecological zones of these localities, nitrogen and especially phosphorus are limiting factors in agricultural production. In this regard, Ouattara *et al.* [7] reported that a period of about twenty years is required to restore fallow soil fertility. Consequently, there has been a push to acquire new arable lands at the expense of natural formations by rural populations [8] [9]. This has led to a pronounced reduction in natural forests and the emergence of numerous degraded lands unsuitable for agriculture and natural regeneration. Additionally, grazing areas for animals have significantly reduced, leading to a gradual reduction in forage potential. Ali *et al.* [5] attributed this to the ongoing risk of conflicts between herders and other users of natural resources. Furthermore, IFPRI [10] noted that over the past decade, the lack of new arable lands and increasing demands for cultivable lands have compelled farmers to shorten fallow periods. This system has proven unsatisfactory in terms of results as it does not guarantee the restoration of initial soil fertility.

In the country, various Soil Defense and Restoration (DRS) techniques have been implemented to enhance soil fertility. Mechanical techniques are predominantly used, such as zaï, stone bunds, and half-moons. Zaï has been shown to improve crop yields by over 100% [11], while stone bunds and half-moons have led to an increase in herbaceous biomass reaching 1000 and 1200 kg/ha compared to only 70 and 110 kg/ha on control plots, respectively [12]. These techniques promote good water retention in the soil and result in significant plant biomass production [13]. In addition to these techniques, those using biological resources, such as mulching, aid in revitalizing soil biological activity and trapping organo-mineral elements. Furthermore, the use of other forestry techniques like assisted natural regeneration, reforestation, and herbaceous seeding, enriches the soil in organic matter and nitrogen, thereby enhancing water retention in the soil [13]-[15]. Additionally, the application of organo-mineral amendments has improved soil fertility, resulting in yield gains of up to 400% for some cucurbit species [16].

Despite the efforts made so far in rehabilitating degraded lands, it is evident that these techniques are labor-intensive and require substantial financial resources [17]. The results are somewhat mixed in terms of system sustainability and adoption rates by producers. Hence, there is a need to explore alternative methods to effectively restore soil fertility. Ouédraogo *et al.* [2] showed that it is possible to sustainably restore soil cover by leveraging the properties of some herbaceous legume species within a dynamic ecosystem. These species possess the advantage of colonizing spaces after first rains due to their significant seed bank buried in the soil [2]. They appear shortly after grasses and have physiological functions that enable them to fix atmospheric nitrogen in the soil through microorganisms such as arbuscular mycorrhizal fungi [18]. This ability to synthesize atmospheric nitrogen makes these legumes efficient green manures, whether associated with crops or buried after their vegetative cycle. Moreover, the biomass produced stimulates the activity of "soil engineers" like termites and earthworms, contributing to overall soil fertility improvement.

In this context, Ouédraogo *et al.* [2] used the fertilization properties of two legume species with interesting phenotypic characteristics on degraded soils to assess their contribution to soil fertility enhancement: *Crotalaria retusa* and *Crotalaria mucronata*. This study was crucial in improving certain physicochemical properties of degraded soils. Although this technique resulted in notable gains in some soil chemical elements such as nitrogen, phosphorus, and carbon, its efficiency within a relatively short period remains unsatisfactory. It is therefore necessary to find an alternative to significantly reduce the restoration time of degraded soil fertility. This involves applying a combination of techniques using the properties of herbaceous legumes in conjunction with organo-mineral amendments to restore the fertility of degraded soils. This study aims to determine the effects of legumes and their association with organo-mineral amendments on the physicochemical properties of degraded soils. The study is based on the hypothesis that the combination of legumes with organo-mineral amendments effectively improves soil fertility.

2. Material and Methods

2.1. Material

Location of study sites: The experiments were carried out in two localities in

Burkina Faso with contrasting pedoclimatic conditions (Figure 1). Yarci, the first locality is a village situated at 80 km in the northwest of Ouagadougou. This village is found in the commune of Arbollé in the Passoré province. The second locality is Noumousso. This village is located at 35 km in the northwest of Bobo Dioulasso, in the Houet province.

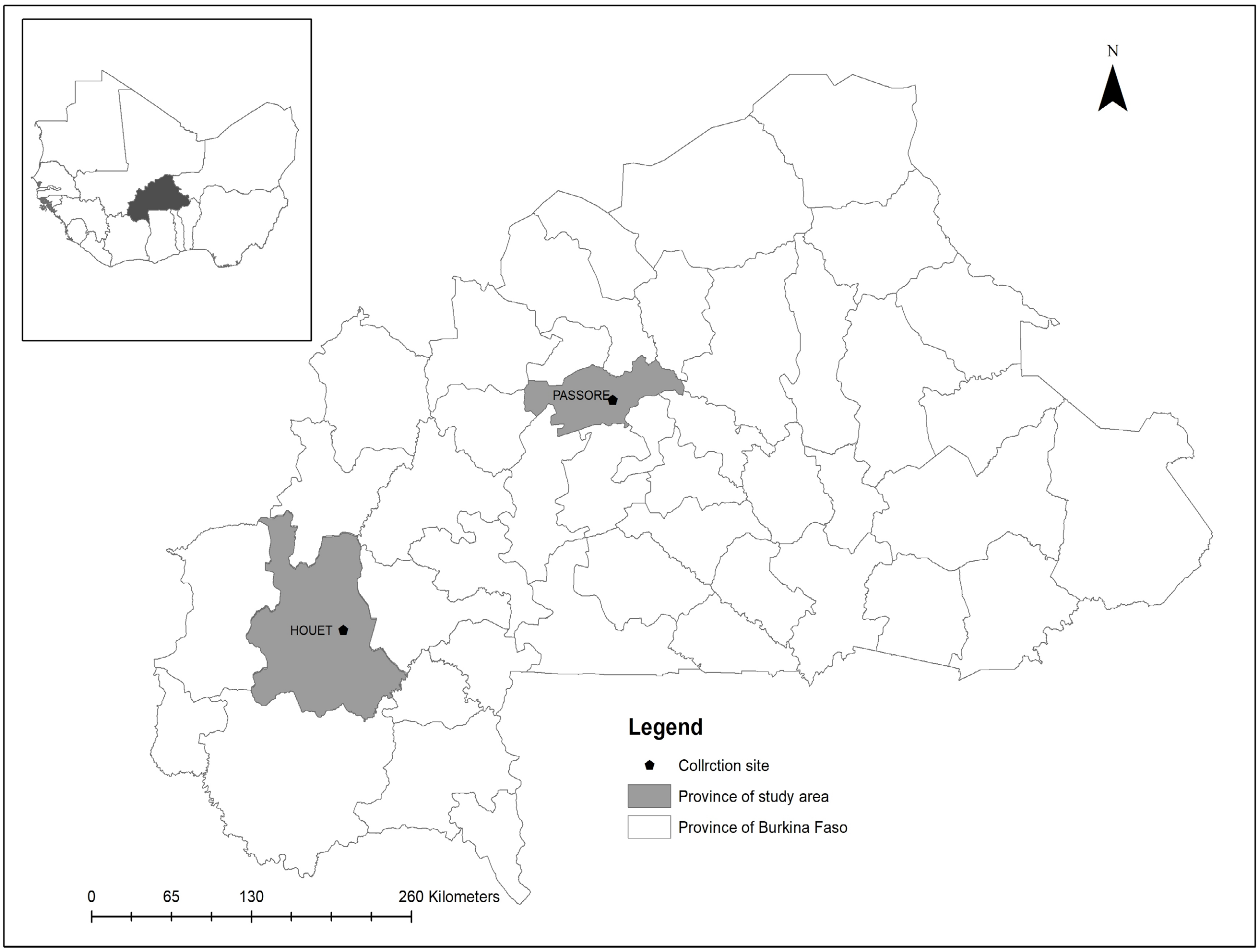


Figure 1. Location of the study sites, showing the two sites localization in Burkina Faso (in West and northern parts).

Pedoclimatic characteristics of the sites: Table 1 summarizes the pedoclimatic characteristics of the two study sites. It shows that the Yarci site is characterized by a North Sudanian climate with an annual rainfall ranging between 600 and 900 mm. The area is flat and marked by a mosaic of tropical ferruginous soils deficient in nitrogen and phosphorus, featuring two toposequences, namely mid and low slopes. The typical vegetation of this site is tiger bush with combretaceae. As for the Noumousso site, the climate is Sudanian with an annual rainfall between 900 and 1300 mm. Similar to the Yarci site, its area includes two toposequences (mid and low slopes) characterized by tropical ferruginous soils that are either poorly leached or leached and deficient in nitrogen and phosphorus. The typical vegetation here is a wooded savanna alternating with shrubby savanna.

Table 1. Pedoclimatic characteristics of the study sites.

Site	Region	Annual Rainfall	Type of Soil
Arbollé	North	600 to 900 mm	Lithisols, ferruginous, little evolved
Noumousso	West	800 to 1100 mm	Tropical ferruginous soils poorly leached or leached, deficient in Nitrogen and Phosphorus

Plants material used: Plants material used are seeds from four ecotypes of two legume species, *Crotalaria retusa* (L.) and *Crotalaria mucronata* (Desv.). This same type of plant material underwent a phenotypic characterization study [2]. The study revealed that these ecotypes possess very interesting phenotypic traits (high biomass) and could play a significant role in soil fertility enhancement through organic matter input. The seeds used include the ecotypes from Gonsé (*C. mucronata* and *C. retusa*), Nasso (*C. retusa*), and Arbollé (*C. mucronata*).

Organo-mineral fertilizers used: The fertilizers used in this study are organic matter (OM) derived from the decomposition of crop residues and animal manure, and Burkina Phosphate (BP). Additionally, a combination (OM + BP) of both types of fertilizers (organo-mineral) was applied. **Table 2** summarizes the chemical composition of these fertilizers.

Table 2. Chemical properties of Burkina phosphate and organic matter.

Designation	BP	OM
	(%)	($mg{\cdot}kg^{-1}$)
Total P	12.35	8.1
P_2O_5	28.3	18.6
Water P	0.19	-
Citrate P	30	-
FeO	1.7	-
CaO	38.3	-
SiO_2	23.33	-
Al_2O_3	2.35	-
K_2O	-	7.2
N	-	8.7
C	-	23.6

BP: Burkina phosphate; OM: organic matter; P: phosphorus; P_2O_5: Phosphorus pentoxide; FeO: ferrous (Iron II) oxide; CaO: Calcium oxide; SiO_2: Silicon dioxide; Al_2O_3: Aluminum oxide; Potassium oxide; N: nitrogen; C: carbon.

2.2. Methods

Experimental design and applied treatments: The following treatments measuring the effects of two factors were applied:

Factor 1: two species of Papilionaceous: the first is *Crotalaria mucronata* (*C. mucronata*). The seeds of this specie were collected in two localities: Gonsé1 and Arbollé corresponding to the ecotypes. The second specie, *Crotalaria retusa* (*C. retusa*) is represented also by two ecotypes collected from Gonsé2 and Nasso.

Factor 2: three amendment levels: zero, organic and mineral amendment. The organic amendment used organic matter derived from the decomposition of crop residues and animal manure and was applied at a rate of 5 t/ha. The mineral amendment used the Burkina Phosphate at 500 kg/ha.

The experiments were laid out in a split-plot design with three replications (Figure 2). The main plot treatment was the Papilionaceous species (represented by the Ecotypes) while the sub-plots treatment was the organo-mineral amendment. The main plot size was 38 m × 16 m (608 m^2) and the sub-plot size was 5 m × 2 m (10 m^2) and a total of 48 plots.

The treatments were: T0: control; T1: Organic matter (OM); T2: OM + Burkina Phosphate (BP); T3: BP.

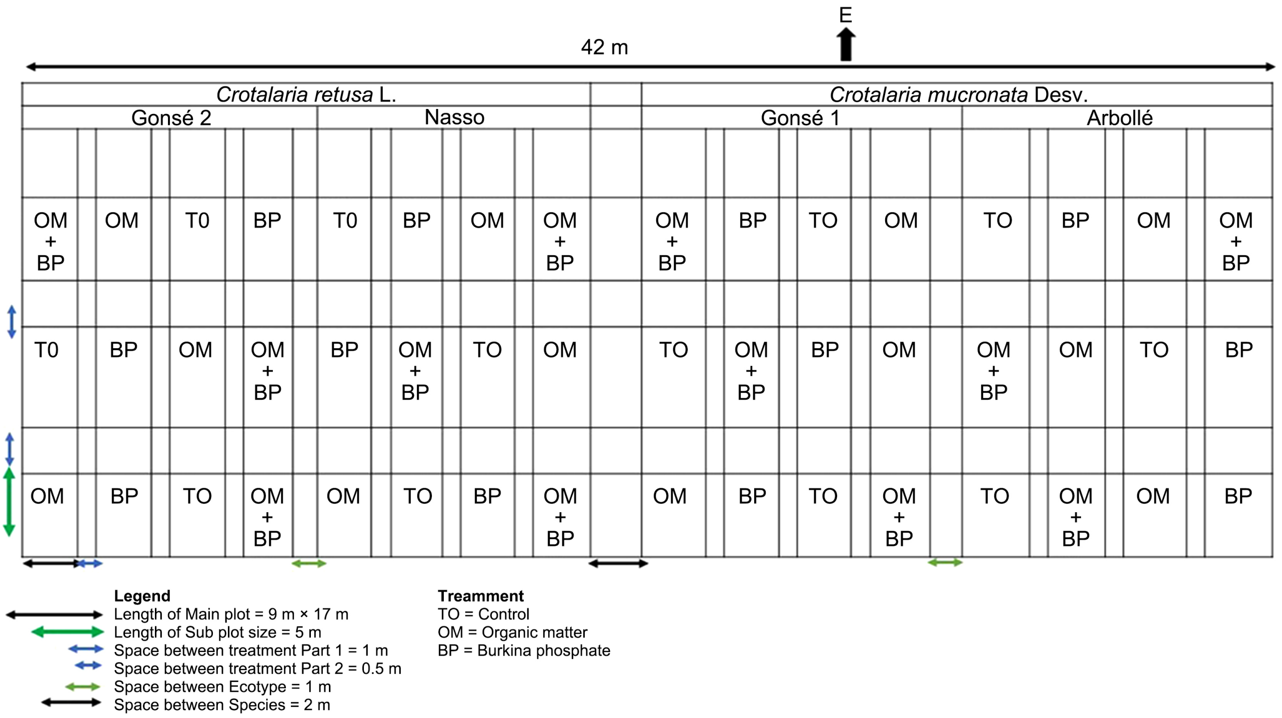


Figure 2. Experiment design including the four Crotalaria ecotypes and the amendments applied.

Husbandry practices: At each site, the plot underwent wet scarification using a manga hoe. Manual leveling was performed prior to plot delimitation. Once the boundaries had been demarcated, organo-mineral amendment was applied at rates of 5 t/ha of organic matter (OM) and 500 kg/ha of Burkina Phosphate (BP).

The same day, 300 Papilionaceous seeds were uniformly distributed on the relevant subplots. No pesticide treatments were done. Measurements based on the quantitative variables were taken on the plants during a period corresponding to their maximum vegetative growth. In addition, fresh biomass was harvested at the same time in the yield squares of 1 m^2.

Soil sampling and analysis: In each locality, five composite soil samples were collected from the 0 - 30 cm depth prior to the implementation of the experiments. After harvest, soil samples were also taken from each treatment at the same depth. All samples were air-dried and sieved to 2 mm. The analyses were conducted at the soil-water-plant laboratory of CREAF Kamboinsé. The determined physicochemical properties included particle size distribution (three fractions), pH, soil organic carbon (C), total nitrogen (Nt), total phosphorus (Pt) and available phosphorus (Pavail), total potassium (Kt), cation exchange capacity (CEC), exchangeable bases (Ca^{2+}, Mg^{2+}, K^+, Na^+), and saturation rate (SR).

Soil organic carbon was determined using the Walkley and Black method [19]. Total nitrogen was measured after mineralization of the samples using the Kjeldahl method [20]. After mineralization, total nitrogen was directly measured using an auto-analyzer. Similarly, total phosphorus and total potassium were measured after mineralization using an auto-analyzer and flame photometer, respectively [21]. Available phosphorus was determined using the Bray I method [22] with a mixed solution of ammonium fluoride (0.03M) and hydrochloric acid (0.025M). The measurement was performed using colorimetry with a spectrophotometer. pH was measured in a distilled water solution using an electronic pH meter [23]. Cation exchange capacity (CEC) and exchangeable bases (Ca^{2+}, Mg^{2+}, K^+, and Na^+) were determined by centrifugation with silver thiourea (0.01M). CEC and exchangeable bases, mainly Ca^{2+} and Mg^{2+}, were measured using an atomic absorption spectrophotometer. K^+ and Na^+ were measured using a flame photometer [21]. The saturation rate is the ratio of the sum of exchangeable bases to CEC.

Assessment of plant biomass: After counting the number of Papilionaceous plants in each subplot, plant harvesting was done at the end of the growing season, at the physiological maturity of the seeds. The stems were gathered into bundles, weighed, and then incorporated into the soil.

Statistical analysis of data: The data collected was entered using the Excel 2019 spreadsheet. Statistical analysis and graph generation were performed using Minitab version 19.1 and GenStat Release 12.1. softwares. The analysis of variance enabled the comparison of means using the Fischer Test at a 5% significance level. This facilitated the identification of ecotypes per specie with high biomass production and the most effective treatments (organo-mineral amendment). Multidimensional statistical methods were employed to establish relationships among ecotypes, soil physicochemical properties, organo-mineral amendment, and plant biomass through Principal Component Analysis (PCA) using the R studio software. This software is an integrated development environment for the R programming language, and is widely used for statistical computing and graphics. It enables users to create interactive plots and visualizations using packages like ggplot2, plotly, and leaflet, enhancing the quality and interactivity of data visualization.

3. Results

3.1. Initial Physico-Chemical Soil Properties

The physico-chemical analysis conducted on the soils sampled before the experiments revealed that, in terms of physical properties, the soils exhibited a sandy-clay texture with higher proportions of sand than clay, particularly at the Noumousso site (**Table 3**). Regarding chemical properties, the analysis indicated that these soils were acidic and deficient in Carbon (C), Nitrogen (Nt), Phosphorus (Pt), exchangeable bases (EB), and Cation Exchange Capacity (CEC) (**Table 4**).

Table 3. Physical properties of the initial soils.

Experiments	Clays (%)	Silts (%)	Sands (%)	Texture
Noumousso Site	14.38	7.84	77.78	Sandy-clay
Arbollé Site	21.57	9.8	68.63	Sandy-clay

Table 4. Chemical properties of the initial soils (0 - 30 cm horizon).

Chemical properties	Initial soil Noumousso	Initial soil Arbollé
pH	5.96	5.17
C (%)	0.65	0.82
N (%)	0.07	0.08
OM (%)	1.12	1.41
C/N	9.70	10.37
Pt (mg/kg)	335.23	589.93
Pavail (mg/kg)	3.21	2.12
Kt (mg/kg)	1487.62	1340.95
Ca^{2+}(meq/100g)	1.72	1.20
Mg^{2+} (meq/100g)	0.76	0.90
K^{+} (meq/100g)	0.44	0.53
Na^{+} (meq/100g)	0.18	0.16
SEB (meq/100g)	3.11	2.85
CEC (meq/100g)	5.31	4.72
SR (%)	58.33	57.33

Initial soil: soil sampled and analysed before the implementation of the experiment; pH: Hydrogen potential; C: Carbon; N: Nitrogen; OM: organic matter; C/N: Carbon/Nitrogen ratio; Pt: Total phosphorus; Pavail: available phosphorus; Kt: Potassium; Ca^{2+}: Calcium ion; Mg^{2+}: Magnesium ion; K^{+}: Potassium ion; Na^{+}: Sodium ion; SBE: Sum of exchangeable bases; CEC: Cation exchange capacity; SR: Saturation rate.

3.2. Effects of Treatments on Soil Physico-Chemical Properties

Table 5 presents the results of the analyses of variance. It showed a highly significant influence of the treatments on soil physico-chemical properties at Noumousso and Arbollé. The analysis revealed that, except for Nt, Pt, Ca^{2+}, and Na^{+}, the effect of the Papilionaceous ecotypes was significant ($p < 0.05$), highly significant ($p < 0.01$), and very highly significant ($p < 0.001$).

It is also noted that the applied organo-mineral amendment had the following effects: significant ($p = 0.019$ for Mg^{2+} at Noumousso), highly significant ($p < 0.005$), and very highly significant ($p < 0.001$) on the other soils chemical properties at both sites, except for sodium ion (Na^{+}) and potassium ion (K^{+}) at Arbollé.

Furthermore, the analyses demonstrated an interaction between the Papilionaceous ecotypes and the organo-mineral amendment. This interaction was found to be significant ($p < 0.05$), highly significant ($p < 0.01$), and very highly significant ($p < 0.001$) on the physico-chemical properties, except for Mg^{2+}, Na^{+}, and SEB at both experimental sites.

Table 5. Results of the analyses of variance.

Noumousso		pH	OM	Nt	C/N	Pt	Pavail	Kt	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	SBE	CEC	TS
			(%)				mg/kg				meq/100g				%
Source de variation	d.f.	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.
Ecotypes	3	<0.001	<0.001	0.801	<0.001	0.084	<0.001	<0.001	0.068	<0.001	<0.001	0.920	0.034	<0.001	<0.001
Traitements	3	0.001	<0.001	<0.001	0.153	<0.001	<0.001	<0.001	<0.001	0.019	<0.001	0.259	0.004	<0.001	0.002
Ecotypes* Traitements	9	<0.001	0.024	<0.001	0.016	0.007	<0.001	<0.001	0.038	0.188	<0.001	0.154	0.065	<0.001	0.006
Arbollé		pH	MOT	N	C/N	Pt	Pavail	Kt	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	SBE	CEC	TS
			(%)				mg/kg				meq/100g				%
Source de variation	d.f.	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.
Ecotypes	3	<0.001	<0.001	<0.001	0.336	0.075	<0.001	<0.001	<0.001	0.009	0.148	<0.001	0.002	<0.001	<0.001
Traitements	3	<0.001	<0.001	<0.001	0.004	<0.001	<0.001	<0.001	<0.001	<0.001	0.265	0.357	<0.001	<0.001	<0.001
Ecotypes* Traitements	9	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.076	<0.001	0.002	<0.001	<0.001	<0.001	<0.001	<0.001

OM: organic matter; N: nitrogen; C/N: carbon/nitrogen ratio; Pt: total phosphorus; Pavail: available phosphorus; Kt: total potassium; s.e.d: standard error of deviation; Pr.: probability; *: no significant difference; **: significant difference; ***: highly significant difference; ****: very highly significant difference.

3.3. Effects of Ecotypes on Soil Fertility

The analysis of variance demonstrated variations in soils physico-chemical properties based on the ecotypes (Table 6): 1) Soils in the experimental plot at Noumousso experienced an increase in Pt content and a decrease in pH, Ca^{2+}, K^+, Na^+, and SEB content; 2) at the Arbollé site, soils experienced an increase in pH, Ca^{2+} and SBE contents, while Pt, K^+, and Na^+ contents decreased; 3) across both experimental sites (Noumousso and Arbollé), the ecotypes contributed to an increase in the C/N ratio, saturation rate, and in organic matter, Pavail, and Mg^{2+} contents. At the Noumousso site, the organic matter content varied between 0.98% (Nasso, *C. retusa*) and 1.21% (Gonsé 1, *C. mucronata*) compared to an initial value of 0.65%. At the Arbollé site, the organic matter content ranged from 1.34% (Gonsé 1, *C. mucronata*) to 1.61% (Nasso, *C. retusa*), compared to an initial value of 0.82%. The C/N ratio ranged between 9 and 12 for all ecotypes, except for Nasso (*C. retusa* at the Noumousso site) which had a C/N ratio of 8.89. The saturation rate varied between 60% - 65% (normal to slightly high) compared to an initial rate of about 58%. However, the total potassium (Kt) content decreased at both sites, while there was a slight decrease in the total nitrogen (Nt) content.

Table 6. Variation of soil physico-chemical properties according to the Ecotypes.

(a)

	Ecotypes	pH	OM	N (%)	C/N	Pt	Pavail	Kt
						mg/kg		
Noumousso	Initial	5.96	1.12	0.07	9.3	335	3.21	1488
	Muc Arb	5.37	1.2	0.07	10.9	365	3.12	1154
	Muc Gon1	5.63	1.21	0.07	11.56	401	4.47	1493
	Ret Gon2	5.52	1.18	0.06	11.01	379	3.97	1117
	Ret Nas	5.87	0.98	0.06	8.89	394	3.06	1147
	s.e.d	0.04	0.05	0.003	0.47	14.81	0.14	53.10
	Pr.	<0.001****	<0.001****	0.801*	<0.001****	0.084*	<0.001****	<0.001****
Arbollé	Initial	5.17	1.41	0.08	10.37	590	2.12	1341
	Muc Arb	6	1.37	0.07	11.39	484	2.62	788
	Muc Gon1	5.59	1.34	0.07	11.17	481	2.71	768
	Ret Gon2	5.63	1.51	0.07	11.65	508	2.85	796
	Ret Nas	5.79	1.61	0.08	11.8	493	2.43	894
	s.e.d	0.032	0.023	0.003	0.367	10.570	0.058	16.830
	Pr.	<0.001****	<0.001****	<0.001****	0.336*	0.075*	<0.001****	<0.001****

Continued

(b)

	Ecotypes	Ca^{2+} (meq/100g)	Mg^{2+} (meq/100g)	K^+ (meq/100g)	Na^+ (meq/100g)	SEB (meq/100g)	CEC (meq/100g)	SR (%)
Noumousso	Initial	1.72	0.76	0.44	0.18	3.11	5.31	58.33
	Muc Arb	1.4	1.04	0.33	0.14	2.91	4.57	60.75
	Muc Gon1	1.45	0.83	0.28	0.14	2.73	4.53	61.25
	Ret Gon2	1.55	0.81	0.42	0.15	2.76	4.56	64
	Ret Nas	1.6	1.04	0.33	0.14	3.13	5.17	60.83
	s.e.d	0.08	0.07	0.02	0.02	0.14	0.11	1.25
	Pr.	0.068*	<0.001****	<0.001****	0.92*	0.034**	<0.001****	<0.001****
Arbollé	Initial	1.2	0.9	0.53	0.16	2.85	4.72	57.33
	Muc Arb	1.62	1.01	0.27	0.1	3.08	4.81	64
	Muc Gon1	1.43	1.09	0.27	0.11	2.85	4.88	61.42
	Ret Gon2	1.5	1.05	0.24	0.14	2.95	4.59	65.5
	Ret Nas	1.69	0.93	0.27	0.14	3.05	4.91	65.25
	s.e.d	0.040	0.045	0.015	0.009	0.061	0.074	0.981
	Pr.	<0.001****	0.009***	0.148*	<0.001****	0.002***	<0.001****	<0.001****

Initial: data collected before the experiment; Muc Arb: Crotalaria mucronata collected at Arbollé; Muc Gon1: Crotalaria mucronata collected at Gonsé1; Ret Gon2: Crotalaria retusa collected at Gonsé2; Ret Nas: Crotalaria retusa collected at Nasso; Ca^{2+}: calcium ion; Mg^{2+}: magnesium ion; K^+: potassium ion; Na^+: sodium ion; SEB: sum of exchangeable bases; CEC: cation exchange capacity; SR: saturation rate; s.e.d: standard error of deviation; Pr.: probability; *: no significant difference; **: significant difference; ***: highly significant difference; ****: very highly significant difference.

3.4. Effect of Organic Amendment on Soil Fertility

Analyses revealed that the application of organic amendment led to variations in soil physico-chemical properties (Table 7). It indicated that: 1) At both sites, compared to the control plot, the application of organo-mineral amendment enhanced soil fertility by improving the physico-chemical properties such as OM, Nt, Pt, Pavail or P_Bray, Kt, EB, and SEB. However, a decrease in soil acidity, an increase in the C/N ratio, and saturation rate were observed. 2) Considering the specific case of the Noumousso site, the application of organic matter alone contributed to decrease Mg^{2+}, K^+, and Na^+ cations contents compared to T0 treatment. 3) For the specific case of the Arbollé site, in comparison to T0 treatment, an increase in soil acidity was observed after the application of organic matter. Furthermore, this application resulted in a decrease in the C/N ratio, Ca^{2+}, Mg^{2+}, K^+, and CEC. Similarly, the application of BP led to a decrease in Mg^{2+} and CEC contents. 4) The application of organo-mineral amendment (OM + BP) resulted in an increase in OM, Nt, Pt, Pavail, Kt, Mg^{2+}, and SR, and a decrease in CEC, K^+, and Na^+ contents at both sites. Ca^{2+} and SEB contents decreased at Noumousso, while they increased at Arbollé.

Table 7. Variation of soil physico-chemical properties according to the organo-mineral amendment applied.

(a)

	Treatments	pH	OM	N (%)	C/N	Pt	Pavail	Kt
						mg/kg		
Noumousso	Initial	5.96	1.12	0.07	9.70	335.23	3.21	1487.62
	T0	5.577b	0.761c	0.04150c	10.24a	252.8c	2.090b	476c
	OM + BP	5.607ab	1.355a	0.07883a	10.51a	467.2a	4.064a	1787a
	OM	5.678a	1.366a	0.08200a	10.36a	338.8b	4.402a	1367b
	BP	5.521b	1.093b	0.05683b	11.25a	480.4a	4.062a	1279b
	s.e.d	0.04	0.05	0.003	0.47	14.81	0.14	53.10
	Pr.	0.001***	<0.001****	<0.001****	0.153*	<0.001****	<0.001****	<0.001****
Arbollé	Initial	5.17	1.41	0.08	10.37	589.93	2.12	1340.95
	T0	5.710bc	0.956d	0.04783c	11.72a	278.3c	2.023d	465.8c
	OM + BP	5.768ab	1.735a	0.08383a	12.10a	594.6a	2.711b	927.8ab
	OM	5.673c	1.651b	0.09108a	10.66b	513.8b	2.398c	967.3a
	BP	5.848a	1.490c	0.07358b	11.54ab	579.9a	3.481a	885.6b
	s.e.d	0.032	0.023	0.003	0.367	10.570	0.058	16.830
	Pr.	<0.001****	<0.001****	<0.001****	0.004***	<0.001****	<0.001****	<0.001****

(b)

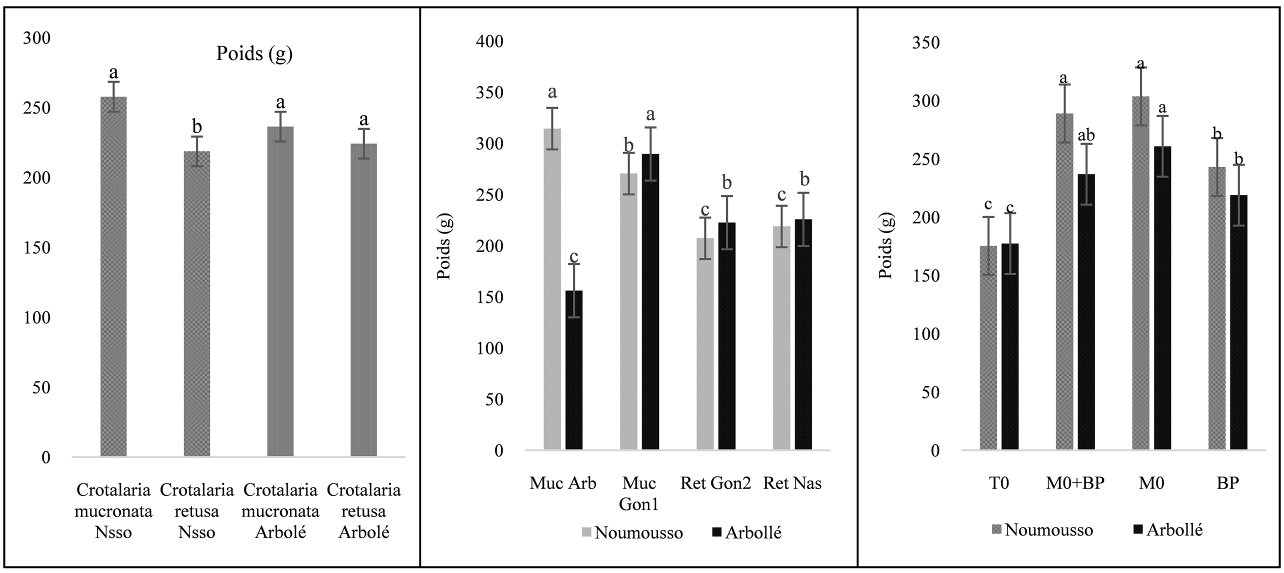
	Traitements	Ca^{2+}	Mg^{2+}	K^+	Na^+	SEB	CEC	SR (%)
		meq/100g						
Noumousso	Initial	1.72	0.76	0.44	0.18	3.11	5.31	58.33
	T0	1.213b	0.9111ab	0.3150b	0.1425a	2.583b	4.663ab	58.92b
	OM + BP	1.544a	1.0239a	0.3633a	0.1517a	3.103a	4.878a	62.75a
	OM	1.632a	0.8116b	0.2950b	0.1217a	2.824ab	4.408b	63.92a
	BP	1.610a	0.9753ab	0.3742a	0.1450a	3.019a	4.878a	61.25ab
	s.e.d	0.08	0.07	0.02	0.02	0.14	0.11	1.25
	Pr.	<0.001****	0.019**	<0.001****	0.259*	0.004***	<0.001****	0.002***

Continued

	Initial	1.20	0.90	0.53	0.16	2.85	4.72	57.33
	T0	1.451b	1.001b	0.2533a	0.1317a	2.906bc	4.819b	61.17c
Arbollé	MO + BP	1.742a	1.192a	0.2825a	0.1175a	3.332a	5.490a	63.42bc
	MO	1.540b	0.966b	0.2583a	0.1175a	2.933b	4.252c	67.17a
	BP	1.516b	0.918b	0.2650a	0.1250a	2.766c	4.637b	64.42b
	s.e.d	0.040	0.045	0.015	0.009	0.061	0.074	0.981
	Pr.	<0.001****	<0.001****	0.265*	0.357*	<0.001****	<0.001****	<0.001****

Initial: data collected before the experiment; T0: absolute control; OM: organic matter; BP: Burkina Phosphate; Ca^{2+}: calcium ion; Mg^{2+}: magnesium ion; K^{+}: potassium ion; Na^{+}: sodium ion; SEB: sum of exchangeable bases; CEC: cation exchange capacity; SR: saturation rate; s.e.d: standard error of deviation; Pr.: probability; *: no significant difference; **: significant difference; ***: highly significant difference; ****: very highly significant difference.

3.5. Effect of Species, Ecotypes, and Organo-Mineral Amendment on Biomass



(a) (b) (c)

Muc Arb: Crotalaria mucronata collected at Arbollé; Muc Gon1: Crotalaria mucronata collected at Gonsé1; Ret Gon2: Crotalaria retusa collected at Gonsé2; Ret Nas: Crotalaria retusa collected at Nasso; T0: absolute control; OM: organic matter; BP: Burkina Phosphate.

Figure 3. Variation of Biomass according to Species (a), ecotypes (b), and Organo-mineral amendment (c) expressing the results obtained in each case.

Statistical analysis revealed a highly significant difference ($p = 0.008$) induced by the two species at the Noumousso site on biomass production. However, at Arbollé, no significant difference ($p > 0.05$) was observed. Figure 3(a) provides an overview of the biomass quantity produced by *Crotalaria mucronata* (257.7 g), which is higher than that produced by *Crotalaria retusa* (218.59 g) at Noumousso.

At the Arbollé site, the difference in biomass production was not significant (236.3 g for *Crotalaria mucronata* and 224.12 g for *Crotalaria retusa*).

Regarding Ecotypes, highly significant differences ($p \le 0.001$) were observed between them. Figure 3(b) indicates that at the Noumousso site, the Arbollé and Gonsé1 Ecotypes (*Crotalaria mucronata*) exhibited the highest biomass production. At the Arbollé site, high production resulted from the *Crotalaria retusa* Ecotypes.

From Figure 3(c), statistical analysis revealed a highly significant difference ($p = 0.001$) between the organo-mineral amendment treatments at the Noumousso site and a significant difference ($p = 0.019$) at the Arbollé site. This figure shows that across both sites, the highest quantity of biomass produced was observed in the OM treatment, followed by the treatment combining organic matter with Burkina Phosphate (OM + BP). The lowest biomass was noted in the control treatment (T0).

3.6. Effects of the "Ecotype-Organo-Mineral Amendment" Interaction on Soil Physico-Chemical Properties and Biomass Production

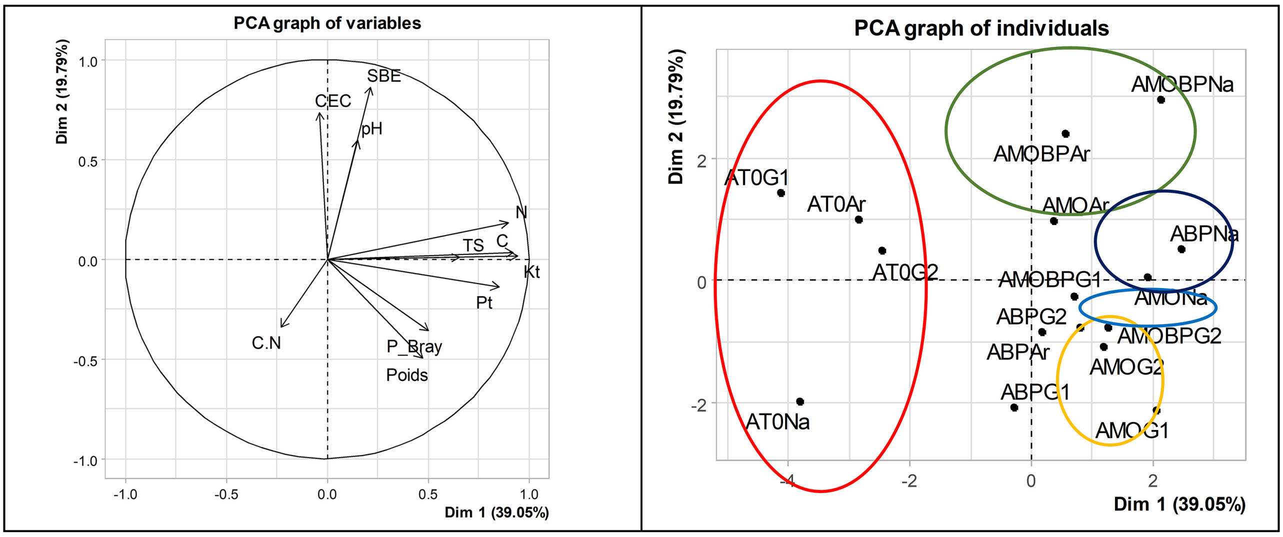
The effects of the ecotype-organo-mineral amendment interaction on soil physico-chemical properties and plant biomass were evaluated using Principal Component Analysis (PCA) at the Arbollé and Noumousso sites (Table 8, Figure 4(a) and Figure 4(b)).

Table 8. Interaction effects on plant biomass (sites of Noumousso and Arbollé).

Ecotypes	Noumousso				Arbollé			
	BP	OM	OM + BP	T0	BP	OM	OM + BP	T0
Arbollé	320.9	396.4	351.7	188.8	142.2	197	147	138
Gonsé1	275.1	272.2	346.8	188	275.1	361.5	347.4	174.6
Gonsé2	171.2	297.2	193.8	167.1	205.1	261.2	234.1	189.6
Nasso	205.3	248.7	263.7	157.7	253.1	223.4	219.1	207.4
Pr.	<0.001				<0.001			

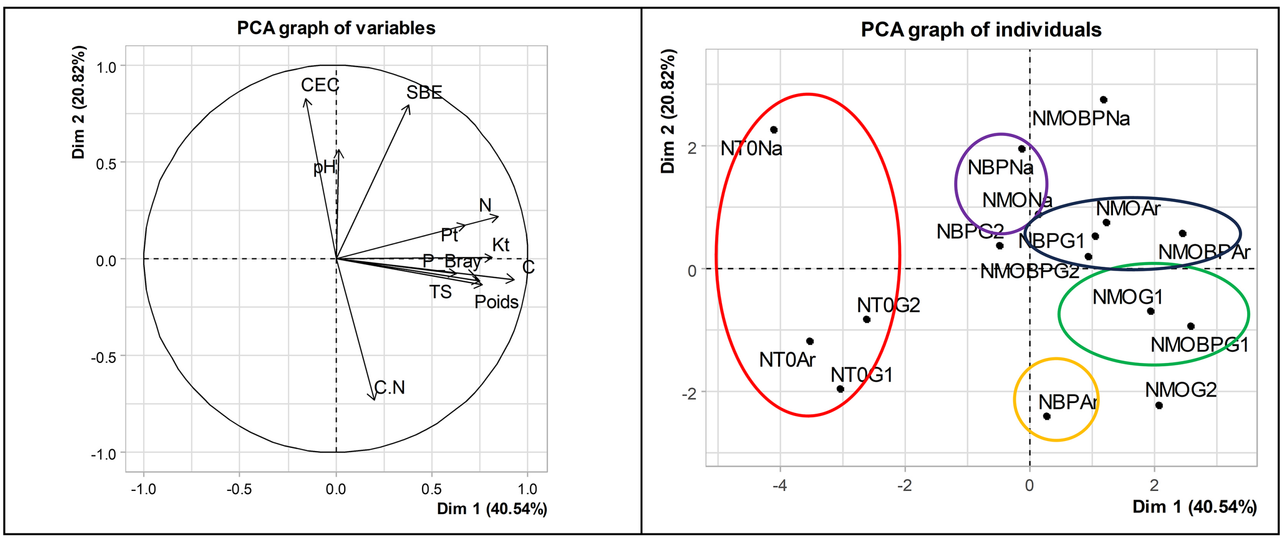
T0: absolute control; OM: organic matter; BP: Burkina Phosphate; Pr.: probability.

Regarding the Arbollé site, PCA related to Papilionaceae Ecotypes, organo-mineral amendment, soil physico-chemical properties, and biomass indicated that the first two axes of the analysis expressed 58.84% of the variability (Figure 4(a)). This analysis highlighted four essential groupings. Group 1, composed of the combination of organic matter with Gonsé1 and Gonsé2, was positively correlated with biomass and available phosphorus (P_Bray). Group 2, consisting of the combination of organic matter and Burkina phosphate with Gonsé2 was positively correlated with total phosphorus (Pt). Group 3, formed by organic matter and the Nasso Ecotype, as well as Burkina phosphate and the Nasso Ecotype, was positively correlated with total potassium (Kt), saturation rate (SR = TS), and nitrogen (Nt). Lastly, Group 4, composed of organic matter and its combination with Burkina phosphate and the Arbollé Ecotype, also the combination of organic matter with Burkina phosphate and the Nasso ecotype, was positively correlated with pH and sum of exchangeable bases (SEB). However, without organo-mineral amendment, all Ecotypes are negatively correlated with all the physico-chemical properties characterized in this study as well as the estimated biomass.



AMOBPAr: Combination of the Arbollé Ecotype with OM + BP at Arbollé; AMOG1: Combination of the Gonsé1 ecotype with OM at Arbollé; ABPG2: Combination of the Gonsé2 Ecotype with BP at Arbollé; AT0Na: Combination of the Nasso Ecotype with T0 at Arbollé; MO: organic matter; Nt: nitrogen; C/N: Carbon-to-nitrogen ratio; Pt: Total phosphorus; Pavail = P_Bray: Available phosphorus; Kt: Total potassium; SBE: Sum of exchangeable bases; CEC: Cation exchange capacity; TS: Saturation rate.

(a)



NMOBPAr: Combination of the Arbollé Ecotype with OM + BP at Noumousso; NMOG1: Combination of the Gonsé1 Ecotype with OM at Noumousso; NBPG2: Combination of the Gonsé2 Ecotype with BP at Noumousso; NT0Na: Combination of the Nas-so Ecotype with T0 at Noumousso; OM: organic matter; Nt: Total nitrogen; C/N: Carbon-to-nitrogen ratio; Pt = P2O5: Total phosphorus; Pavail = P_Bray: Available phosphorus; Kt = K2O: Total potassium; Ca2+: Calcium ion; Mg2+: Magnesium ion; K+: Po-tassium ion; Na+: Sodium ion; SBE: Sum of exchangeable bases; CEC: Cation exchange capacity; TS: Saturation rate.

(b)

Figure 4. (a) Principal Component Analysis among Ecotypes, Organo-mineral amendment, soil physico-chemical properties, and biomass (site of Arbollé) showing the link among the four components; (b) Principal Component Analysis among Ecotypes, Organo-mineral amendment, soil physico-chemical properties, and biomass (site of Noumousso) showing the link among the four components.

The principal component analysis concerning the Noumousso site and the link among Papilionaceous Ecotypes, organo-mineral amendment, soil physicochemical parameters, and biomass is presented in **Figure 4(b)**. The first two axes of the analysis expressed 61.36% of the variability with four distinct groups. Group 1, composed of organic matter and the Gonsé1 Ecotype, and the combination of organic matter with Burkina phosphate and Gonsé1 Ecotypes, was positively correlated with biomass, saturation rate, carbon, and available phosphorus. Group 2, including Burkina phosphate and the Arbollé Ecotype, was positively correlated with the C/N ratio. Group 3, composed of organic matter and the Arbollé Ecotype, the combination of organic matter with Burkina phosphate and the Arbollé Ecotype, the combination of organic matter with Burkina phosphate and Gonsé2 Ecotypes, and Burkina phosphate + Gonsé1 Ecotypes, was positively correlated with Kt, Nt, and Pt. Group 4, composed of Burkina phosphate and the Nasso Ecotype, organic matter and the Nasso Ecotype, was positively correlated with pH. It was also observed that at the Noumousso site, without the addition of organo-mineral amendment, all Ecotypes were negatively correlated with all the physico-chemical properties characterized in this study as well as the estimated biomass. These results underscore the importance of organo-mineral amendment in improving soil properties and the growth of *C. mucronata* and *C. retusa* plants.

4. Discussion

This study showed that soils of the experimental plots exhibited an initial state characterized by an acidic pH and a sandy-clay texture. Consequently, low levels of chemical properties such as Carbon (C), Nitrogen (Nt), Phosphorus (Pt), and exchangeable bases were found. In addition, the low observed cation exchange capacity (CEC) is characteristic of soils experiencing a loss of chemical properties, indicating the low fertility level of these soils under study. These findings are consistent with those of Hassimiou-Halidou *et al.* [24] in a study conducted in Niger where they demonstrated that acidity, sandy texture, and low levels of carbon, nitrogen, and phosphorus reflect the degraded soils. Therefore, these soils under study were deficient in nutrients. However, the experiments revealed that the application of Ecotypes, organo-mineral amendments, and their interaction significantly increased soils chemical properties, indicating an improvement in soil fertility. The use of Ecotypes helped reduce soil acidity, thereby promoting cation exchanges and leading to gains in soil nutrients such as C, N, and P. These results demonstrated the effective root symbiosis activity of these legume Ecotypes with mycorrhizal fungi. This process revealed soils fertility level. Similar observations have been made in studies on soil fertility restoration through the use of woody legumes (*Acacia senegal*) and herbaceous legumes (*Crotalaria retusa* and *Crotalaria mucronata*) respectively by Hassimiou-Halidou *et al.* [24] and Ouédraogo *et al.* [2].

Regarding the contribution of organo-mineral amendment to the soils with ecotypes, variations in some chemical properties were noted across all sites. At Noumousso, a decrease in Ca^{2+} ions and sum of exchangeable bases (SEB) resulted in a reduction in soil acidity. But at Arbollé, an increase in Ca^{2+} content and SBE led to an increase in soil acidity. This phenomenon indicates that in the presence of neutral or alkaline soils, phosphate ions are converted into Calcium phosphate. In this context, Randriamanantsoa [25] reported that the solubility of phosphate increases with pH, while the solubility of Calcium phosphate decreases with pH. Furthermore, this phenomenon could be explained by the proportions of clay and sand at the two sites. Indeed, the soils at the Noumousso site, characterized by a very low proportion of clay and a high proportion of sand, allowed for the fixation of Calcium ions. On the other hand, at Arbollé, the high proportion of clay favored the fixation of exchangeable bases (especially Ca^{2+}), which contributed to the decrease in soil acidity.

Considering the combined effect of Ecotypes and organo-mineral amendment, it appears that there was increase in initial soil chemical properties. The interaction led to a reduction in soil acidity and a very significant increase in nitrogen, carbon, and available phosphorus contents. This facilitated the decrease in soil acidity, resulting in improved cation exchange capacity (CEC) and potentially enhancing soil biological activity. These findings agree with those of Hassimiou-Halidou *et al.* [24] and Ouedraogo *et al.* [2] on soil restoration technics using legumes. Furthermore, this interaction between Ecotypes and organo-mineral amendment resulted in the availability of phosphorus, potassium and magnesium in the soil. It could also lead to a decrease in the solubilization of some minerals that may cause toxicities such as aluminum, copper, and manganese. The legume Ecotypes investigated contributed remarkably to improving the physico-chemical properties of the soils on both sites. These results confirm that the use of legume Ecotypes is of great ecological importance [26] and contributes to the restoration of degraded soils [27]. According to Akedrin *et al.* [28], the use of legumes appears to be essential for rebuilding the humus horizon, thereby able of restoring soil fertility and influencing the growth of non-nitrogen-fixing crops. This observation was made in Burkina Faso through the study of Ouedraogo *et al.* [2], as well as in other countries such as Niger [24] and Ivory Coast [28].

Furthermore, the ecotypes induced an increase in carbon content through their high biomass production. This becomes possible after the completion of the plants' vegetative cycle. The biomass produced returns to the soil in the form of organic matter after complete decomposition, contributing in improving soils physico-chemical properties. These data confirm those of Hassimiou-Halidou *et al.* [24], Tanoh *et al.* [29], and Ouédraogo *et al.* [2], who observed that legumes are sources of potentially mineralizable organic matter, hence a source of nutrients such as nitrogen and phosphorus.

The amendment using organic matter and Burkina Phosphate has led to a significant improvement in soils physico-chemical properties across both sites. This application resulted in a gain of soil nutrients in these sites. Several studies have demonstrated the necessity of using composts enriched with Burkina Phosphate to enhance the soil's nutrient balance, feed the soil microbial populations, and protect plants against pathogens [30]-[32]. In this study, the application of organo-mineral amendment contributed to improving biomass production across all ecotypes. At the Noumousso site, the increase in biomass due to BP, OM, and OM + BP compared to the absolute control T0 was respectively 38.6%, 64.8%, and 73.1%. At the Arbollé site, these percentages were 23.4%, 33.5%, and 47% respectively. The high amount of biomass produced resulted from the treatment involving organic matter combined with Burkina Phosphate, while the lowest production resulted from the treatment involving only Burkina Phosphate. This difference could be attributed to the fact that Burkina Phosphate provides only one fertilizing element (Phosphorus), which is not directly available to plants. This result aligns with that of Sagnon *et al.* [33], who reported in a study on sorghum that the lowest grain yield is induced by the application of Burkina Phosphate compared to the use of NPK and compost enriched with Burkina Phosphate. However, they observed that the combination of compost enriched with Burkina Phosphate leads to good yields. The increase in yield using the combination of OM + BP is almost equal to the yield induced by the application of NPK. This is due to the abundance of microorganisms in the soil amended with compost associated with Burkina Phosphate.

This study also highlighted the influence of the rainfall patterns in the agro-climatic zones on the amount of biomass produced. At Noumousso, the amount of biomass produced was 1.5 times greater than that produced at Arbollé. The low amount of biomass produced at Arbollé is also thought to be due to the sudden cessation of rainfall, which led to early desiccation and loss of plant biomass at this site.

5. Conclusion

This study assessed the contribution of two legume species (*Crotalaria mucronata* and *C. retusa*) represented by the four studied Ecotypes on soil fertility improvement. The organo-mineral amendment provided an understanding of its effect and that of its interaction (ecotypes-organo-mineral amendment) on soil physico-chemical properties. Among all the tested treatments, the most significant gains were observed with the "ecotypes-organo-mineral amendment" combination. This interaction has been highly beneficial in enhancing soil nutrients across both sites. This observation supports the hypothesis that combining legumes with organo-mineral amendments effectively improves soil fertility. This combination helped reduce soil acidity, increase nitrogen, carbon, and available phosphorus contents. Therefore, using these legume species in combination with compost enriched with Burkina Phosphate could potentially improve the soil's resilience to environmental stresses and promote sustainable agricultural practices by reducing the need for synthetic fertilizers. It could also be an alternative for enhancing the fertility of degraded soils.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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