International Journal of Environmental & Agriculture Research

IJOEAR

www.ijoear.com

ISSN 2454-1850

Volume-9, Issue-8, August 2023

Preface

We would like to present, with great pleasure, the inaugural volume-9, Issue-8, August 2023, of a scholarly journal, *International Journal of Environmental & Agriculture Research*. This journal is part of the AD Publications series *in the field of Environmental & Agriculture Research Development*, and is devoted to the gamut of Environmental & Agriculture issues, from theoretical aspects to application-dependent studies and the validation of emerging technologies.

This journal was envisioned and founded to represent the growing needs of Environmental & Agriculture as an emerging and increasingly vital field, now widely recognized as an integral part of scientific and technical investigations. Its mission is to become a voice of the Environmental & Agriculture community, addressing researchers and practitioners in below areas.

Environmental Research:

Environmental science and regulation, Ecotoxicology, Environmental health issues, Atmosphere and climate, Terrestric ecosystems, Aquatic ecosystems, Energy and environment, Marine research, Biodiversity, Pharmaceuticals in the environment, Genetically modified organisms, Biotechnology, Risk assessment, Environment society, Agricultural engineering, Animal science, Agronomy, including plant science, theoretical production ecology, horticulture, plant, breeding, plant fertilization, soil science and all field related to Environmental Research.

Agriculture Research:

Agriculture, Biological engineering, including genetic engineering, microbiology, Environmental impacts of agriculture, forestry, Food science, Husbandry, Irrigation and water management, Land use, Waste management and all fields related to Agriculture.

Each article in this issue provides an example of a concrete industrial application or a case study of the presented methodology to amplify the impact of the contribution. We are very thankful to everybody within that community who supported the idea of creating a new Research with *IJOEAR*. We are certain that this issue will be followed by many others, reporting new developments in the Environment and Agriculture Research Science field. This issue would not have been possible without the great support of the Reviewer, Editorial Board members and also with our Advisory Board Members, and we would like to express our sincere thanks to all of them. We would also like to express our gratitude to the editorial staff of AD Publications, who supported us at every stage of the project. It is our hope that this fine collection of articles will be a valuable resource for *IJOEAR* readers and will stimulate further research into the vibrant area of Environmental & Agriculture Research.

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Agricultural Sciences	
Soil Science	Plant Science
Animal Science	Agricultural Economics
Agricultural Chemistry	Basic biology concepts
Sustainable Natural Resource Utilisation	Management of the Environment
Agricultural Management Practices	Agricultural Technology
Natural Resources	Basic Horticulture
Food System	Irrigation and water management
Crop Production	
Cereals or Basic Grains: Oats, Wheat, Barley, Rye, Triticale, Corn, Sorghum, Millet, Quinoa and Amaranth	Oilseeds: Canola, Rapeseed, Flax, Sunflowers, Corn and Hempseed
Pulse Crops: Peas (all types), field beans, faba beans, lentils, soybeans, peanuts and chickpeas.	Hay and Silage (Forage crop) Production
Vegetable crops or Olericulture: Crops utilized fresh or whole (wholefood crop, no or limited processing, i.e., fresh cut salad); (Lettuce, Cabbage, Carrots, Potatoes, Tomatoes, Herbs, etc.)	Tree Fruit crops: apples, oranges, stone fruit (i.e., peaches, plums, cherries)
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Mapping Bioavailability of Mineral Elements under Sugarcane Cultivation: Case of the Soils of the Integrated Agricultural Unit of Zuenoula (Centre-West Côte d'Ivoire)

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Received:- 01 August 2023/ Revised:- 20 August 2023/ Accepted:- 28 August 2023/ Published: 31-08-2023

Abstract**—** *The knowledge of the bioavailability of mineral elements in the soil to plants is of great agronomic interest for the improvement of agricultural production. For this purpose, soil samples were taken from the top 60 cm of the soil in the three different sectors of the sugarcane plantations at the Zuenoula integrated agricultural unit. These samples underwent physico-chemical analyses in the laboratory according to standard procedures. The results of the soil analyses are compared with the reference values for sugarcane. All these values were georefrenced through the coordonates of the corresponding sample. These georeferenced values were processed by interpolation methods with ArcGis software to obtain thematic maps of the bioavailability of these nutrients. The results obtained show that the texture was silty in all soil layers considered. They are not very acidic. nitrogen levels are low. Organic carbon and Phosphorus contents are low to moderate. The mineralisation of organic matter is relatively normal. The adsorbent complex was slightly to moderately saturated. Various ratios (Ca/Mg and Mg/K) point to nutritional imbalances. Thematic mapping of these different parameters showed a deficiency in mineral elements, at high percentages (≥ 90%) in the different soil layers. This reflects the expression of a generally low to medium soil fertility status. This would require the correction of these limiting factors for optimal mineral nutrition of sugarcane. Thus, sustainable soil fertility management requires a good knowledge of the physico-chemical parameters of soils cultivated with sugarcane. Spatial information technology leading to detailed mapping of soil, is an important tool to achieve this.*

Keywords**— Sugar cane, mapping, soil, bioavailability, mineral elements, Côte d'Ivoire.**

I. INTRODUCTION

Soil is a fundamental aspect of land resources and is the foundation for agricultural development and environmental sustainability. It is an important factor for the survival of organisms in all living environments (Fox *et al.*, 2008). Its evolution is linked to the combined action of climate and vegetation, leading to both geochemical and structural evolution. To this 'natural' effect adds the influence of the type of land use on its properties (Bigorre, 2000). Maintaining and even increasing soil fertility is an important issue (Sanchez, 2002). A study by Tittonell *et al* (2007) clearly demonstrated the impact of soil fertility, climatic conditions and soil fertility management models on crop yields in Africa. In sub-saharan Africa, widespread loss of soil fertility is one of the main causes of declining agricultural productivity and food insecurity (Pieri, 1989; Stoorvegel and Smaling, 1990; de Ridder *et al.* 2004), so improving soil fertility and agricultural productivity are two priority objectives of agricultural policy in West Africa (CORAF/WECARD, 2008). Thus, the recent decline in sugar production in Côte d'Ivoire is thought to be due to a decline in soil fertility in sugarcane cultivation (Bouadou, 2014; Yao, 2017). Sustainable management of soil fertility in industrial sugarcane farming would therefore require a good knowledge of the physical, chemical and hydrodynamic characteristics of soils. Spatial information technology, including mapping, would be an important tool to achieve this.

The updated mapping of nutrient availability in soils under sugarcane crops was carried out on the plots of the Sucrivoire at the integrated agricultural unit in Zuénoula with the aim of making new fertilisation recommendations. This study specifically aims at the sustainable management of soil fertility, through the knowledge and geolocation of soil fertility levels. This required knowledge of physical and chemical parameters, as well as certain balances between mineral elements. These observations were made according to soil depth levels corresponding to the progression of the volume of soil explored by the roots according to the phenological stages of the plant.

II. MATERIAL AND METHODS

2.1 Description of the study site

The Integrated Agricultural Unit of Zuénoula is located at an altitude of 209 m above sea level, between latitudes 7°30 and 7°40 North, and longitudes 6°5 and 6°15 West (Péné and Assa, 2003). It is located in the Marahoué region in the centre-west of Côte d'Ivoire, precisely straddling the departments of Zuénoula in the south and Vavoua in the west. The UAI of Zuénoula is bordered to the north by the department of Kongasso. It is located 25 km from the town of Zuénoula and is bordered to the east by the right bank of the Marahoué or Red Bandama River. It is a transition zone between forest and savannah. Over more than three decades (updated to 2019), the area records an average annual rainfall of 1179 mm. The Integrated Agricultural Unit of Zuénoula currently covers an area of almost 12,900 hectares, subdivided into 3 sectors (A, B and C). A sprinkler irrigation system with rotating booms is used, hence the name "Pivot" given to the circular plots (Figure 1). The average monthly temperatures vary between 24°C and 31°C. The soils are mainly composed of Cambisol, Gleysol and Arenosols according to the World Soil Resources Database classification (version 2015) (Bouadou, 2014 and Yao, 2017).

2.2 Sampling

The soil survey was carried out through pits, at a scale of 1:10,000, i.e. one observation every 100 metres. The pits were opened at right angles (90°). They were 1.20 meter deep, 1 meter long and 0.80 meter wide. The distribution of the pits corresponded to a regular grid pattern. Samples were collected from the soil horizons (0-20 cm, 20-40 cm and 40-60 cm) for laboratory analysis.

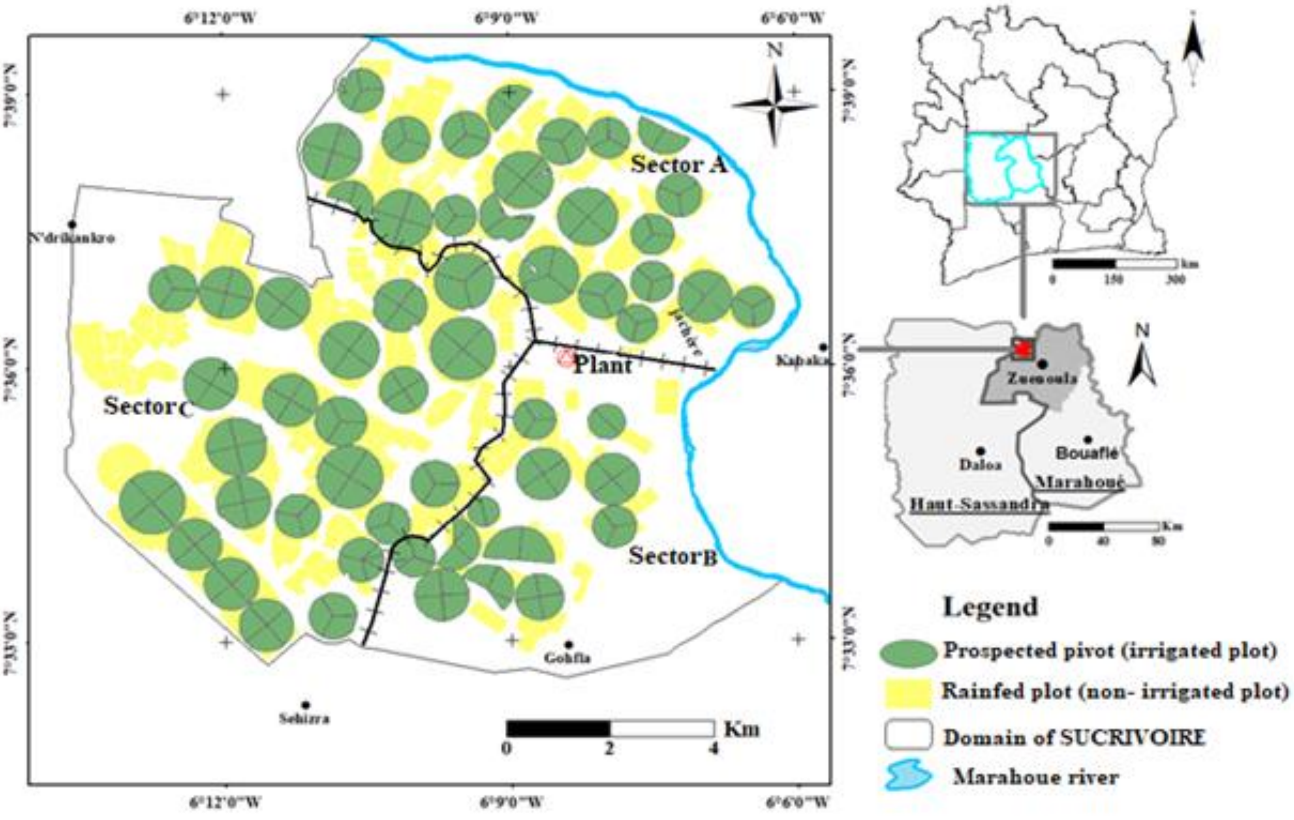

FIGURE 1: Location map of the Sucrivoire-Zuénoula Integrated Agricultural Unit

2.3 Laboratory methods

The soil samples taken were dried in the shade in the laboratory. After drying, the fine soil was sieved through a 2 mm sieve. For the physical and chemical analyses, the samples were recomposed into three horizons, i.e. 0-20 cm, 0-40 cm and 0-60 cm, to take into account the evolution of the plant's roots according to the different stages of growth.

The Robinson-Köln pipette method (Fournier *et al.*, 2012) was used to determine the different particle size fractions. The pH was determined by the electrometric method, in a soil/water ratio of 1/2.5 (Mathieu and Pieltain, 2003). Total organic carbon was determined by the Walkley-Black method (Nelson and Sommer, 1982). The total nitrogen content was obtained by Kjeldahl distillation (Bremner and Mulvaney, 1982). Available phosphorus was determined by Olsen method. Exchangeable bases (Ca^{2+}, Mg^{2+}, K^{+}) were determined by extraction with ammonium acetate buffered at pH 7, followed by saturation with NaCl for the determination of the cation exchange capacity (CEC) and the determination of these different cations.

2.4 Mapping method

Thematic maps were drawn up from geo-referenced values (using GPS) of the physical and chemical parameters of the soil, namely pH, organic carbon, total nitrogen, total phosphorus, available phosphorus, exchangeable bases and CEC. These geo-referenced values were processed by interpolation methods in ArcGis software. The results of the soil analyses were compared to the reference values for sugarcane (Pouzet *et al.*, 1997). In this way, the requirements of sugarcane for soil nutrients (N, P, K, Ca, Mg and organic matter) were mapped.

2.5 Statistical analysis

The analysis focused on different soil profile horizons (0-20; 20-40; 40-60 cm) of the studied pivots. It consisted of a simple descriptive statistical analysis to determine the general average of the soil, its coefficient of variation of physical and chemical parameters. The one-factor analysis of variance (ANOVA) was used to test the hypothesis of an influence of depth on the physico-chemical properties of the soil. The Tukey HSD (Honest Significant Differences) test was used to perform multiple comparisons of means at the 5% threshold. These analyses were carried out using XLSTAT (2016) software.

III. RESULTS

3.1 Granulometry and texture at increasing depths (0-20, 0-40 and 0-60cm)

Although the values recorded in Table I do not show significant differences, it does show an evolution, either increasing or decreasing according to the different soil layers.

For the clay content, it increased with depth. These values are 19%, 21% and 23%, respectively for the 0-20, 0-40 and 0-60 cm horizons.

As for the silt content, it showed a decreasing trend for these different depths, with values of 39%, 36% and 32% respectively.

The sand content showed a similar trend to the clay. Thus, for the different depths considered, the values were 39%, 40% and 42% respectively.

Placed in the triangular diagram of soil textural classes, all these values indicate silty textured soils.

TABLE 1
GRANULOMETRIC COMPOSITION OF SOILS ACCORDING TO HORIZONS

Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Textural class
0-20	19,167 a	39,279 a	39,142 a	Loam
0-40	21,111 a	36,308 a	40,167 a	Loam
0-60	22,812 a	32,223 a	42,731 a	Loam
Mean	21,030	35,937	40,680	**Loam**
Mean Pr > F	0,077	0,208	0,610	
Significance	ns	ns	ns	

Pr > F: Probability associated with the ANOVA test; MG: overall mean; Means assigned the same letter in the same column are not significantly different at the a=0.05 threshold. ns: not significant; *: significant; **: highly significant; ***: very highly significant

3.2 Availability of mineral elements for the 0-20, 0-40 and 0-60 cm horizons

3.2.1 Organic nitrogen, carbon, organic matter and C/N ratio

A highly significant difference was observed between the contents of total nitrogen, organic carbon and organic matter (Table III). The mean values were decreasing, from 1.232 to 0.778 $g.kg^{-1}$ for total nitrogen, 12.304 to 7.789 $g.kg^{-1}$ for organic carbon and 21.212 to 13.429 $g.kg^{-1}$ for organic matter, respectively for 0-20, 0-40 and 0-60 cm horizons. However, nitrogen levels were generally low (<1.5 $g.kg^{-1}$). This low nitrogen content can be observed in 95.79% of the sugarcane area, for the first 20 cm of soil (Fig. 2), and reaches 99% when moving to greater depths, i.e. 0-40 and 0-60 cm (Fig. 3, Fig. 4).

For organic carbon, fertility levels are medium (10-15 $g.kg^{-1}$) for the horizon (0-20cm) and become low (<10 $g.kg^{-1}$) with depths (0-40 and 0-60 cm). This trend would be the same for soil organic matter.

The C/N values of the horizons (0-20, 0-40 and 0-60cm) showed an increasing trend from 9 to 10. This trend revealed a significant difference between the layers of soil. These values indicate a normal mineralisation for all these different soil horizons.

3.2.2 Acid-base status

The pH_{water} of the soils of the different horizons (0-20, 0-40 and 0-60cm) varied between 6.47 to 6.32 (low acidity) and showed an acid tendency with depth. However, this acidity trend did not show a significant difference between the different horizons. The pH_{KCl} followed the same trend. As for the variation between the two types of pH (ΔpH), it was in general higher than 1 (Table III).

3.2.3 Available phosphorus (Pass) and total phosphorus (Ptot)

The total phosphorus and available phosphorus contents for the soil horizons (0-20, 0-40 and 0-60 cm) did not show significant differences. However, a downward trend in the values was noted with depth. Thus, the means of assimilable phosphorus content ranged from 29.167 $mg.kg^{-1}$ in the surface horizon (0-20 cm) to 15.833 $mg.kg^{-1}$ in the deep horizon. The same applies to total phosphorus content, which varies from 406.917 $mg.kg^{-1}$ to 322.083 $mg.kg^{-1}$.

For such values, even if the level of fertility appears high to medium, on about 70 to 87% of the areas, it is important to note that the proportion of soils with low phosphorus fertility on the study site starts from 12.04% of the areas with the 0-20 cm layer (Fig. 5) and reaches a higher proportion (30.85%) with the deeper layers (0-60 cm) (Fig. 6, Fig. 7).

3.2.4 Soil adsorbent complex

The different parameters characterising the adsorbent complex, all showed decreasing values with depth (Table IV). For the soil horizons (0-20, 0-40 and 0-60cm), the values of CEC, Mg^{2+} and saturation rate (V) observed did not show any significant difference (P= 0.453; 0.885 and 0.367) between the means. But, for the CEC, the value of the first 20 centimeters (7.933 $cmol.kg^{-1}$) of soil, is slightly higher than global means (7,569 $cmol.kg^{-1}$), and those of the the other horizons are low than this global average. On the other hand, the Ca^{2+} contents showed highly significant differences for values varying from 3.5 to 2.7 $cmol.kg^{-1}$. It's the same reality for potassium (K^{+}) content, whose levels decrease significantly with depth, from 0.3 to 0.1 $cmol.kg^{-1}$.

The fertility levels in potassium represented 98% of the areas cultivated with sugarcane, by considering the 0-20 cm horizon (Fig. 8). This proportion drops slightly to 92% for the 0-60 cm horizon (Fig. 9, Fig. 10).

3.3 Some chemical balances

3.3.1 Ca/Mg ratio

The results showed that the Ca/Mg ratios of the soils in the 0-20, 0-40 and 0-60 cm horizons varied from 2.48 to 2.61 (Table IV). The results showed an increasing trend with increasing depth. However, this trend was not statistically significant.

3.3.2 Mg/K ratio

The Mg/K ratio is also characterised by an increasing trend from the 0-20 cm horizon through the 0-60 cm horizon. It varies from 7.20 to 10.16 on average (Table IV). But this trend did not show any statistically significant difference.

TABLE 2
RATINGS FOR SOIL FERTILITY CLASSES (ESU, 1991)

Parameters	Low	Medium	High
organic matter (MO) ($g.kg^{-1}$)	<10	10-15	>15
nitrogen (N) ($g.kg^{-1}$)	<1.5	1.5-2.0	>2.0
Organic carbon (C) ($g.kg^{-1}$)	<10	10-15	>15
C/N	<8	8-12	12-15
Available phosphorus (P) (mg $Kg^{-1)}$	<10	10-20	>20
Exchangeable K ($cmol.kg^{-1}$)	<0.15	0.15-0.40	>0.40
Exchangeable Ca ($cmol.kg^{-1}$)	<2	2-5	>5
Exchangeable Mg ($cmol.kg^{-1}$)	<0.3	0.3-1.0	>1.0
CEC ($cmol.kg^{-1}$)	<6	6-12	>12

TABLE 3
PHYSICO-CHEMICAL COMPOSITION OF SOILS ACCORDING TO DIAGNOSTIC HORIZONS

Depth (cm)	pH_{water}	pH_{Kcl}	Δ pH	N $g.kg^{-1}$	C $g.kg^{-1}$	C/N	M.O gkg^{-1}	P assi. $mg.kg^{-1}$	P total $g.kg^{-1}$
0-20	6,472 a	5,383 a	1,089 a	1,232 a	12,304 a	9,969 a	21,212 a	29,167 a	406,917 a
0-40	6,346 a	5,152 a	1,194 a	0,881 b	8,696 b	9,778 a	14,991 b	17,111 a	297,333 a
0-60	6,325 a	5,096 a	1,230 a	0,778 b	7,789 b	10,007 a	13,429 b	15,833 a	322,083 a
Average	6,381	5,21	1,171	0,963	9,596	9,918	16,544	20,704	342,111
Mean Pr > F	0,547	0,125	0,206	0,0002	0,002	0,067	0,0001	0,270	0,083
Significance	ns	ns	ns	***	***	*	***	ns	ns

Means assigned the same letter in the same column are not significantly different at the a=0.05 threshold ns: not significant; *: significant; **: highly significant; ***: very highly significant.

TABLE 4
CHEMICAL COMPOSITION OF SOILS ACCORDING TO DIAGNOSTIC HORIZONS

Depth (cm)	CEC(T) $cmol.kg^{-1}$	K^+ $cmol.kg^{-1}$	Mg^{2+} $cmol.kg^{-1}$	Ca^{2+} $cmol.kg^{-1}$	Saturation %	Ca/Mg	Mg/K
0-20	7,933 a	0,304 a	1,904 a	3,564 a	66,810 a	2,479 a	7,719 a
0-40	7,322 a	0,219 b	1,841 a	2,982 b	61,734 a	2,621 a	9,597 a
0-60	7,450 a	0,199 b	1,838 a	2,771 b	59,215 a	2,519 a	10,164 a
Average	7,569	0,241	1,861	3,106	62,586	2,540	9,160
Mean Pr > F	0,453	0,045	0,885	0,008	0,367	0,964	0,244
Significance	ns	ns	ns	**	ns	ns	ns

Means assigned the same letter in the same column are not significantly different at the a=0.05 threshold ns: not significant;*: significant; **: highly significant; ***: very highly significant.

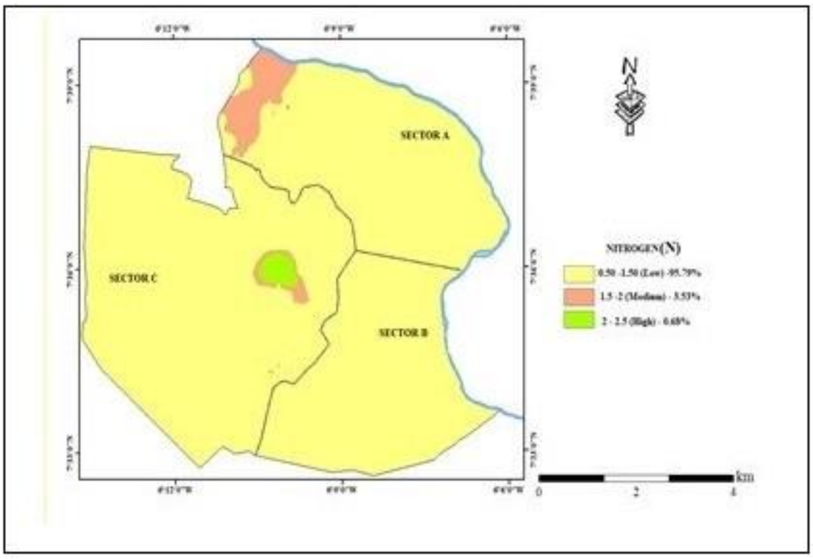

FIGURE 2: Spatial evolution of nitrogen in the 0-20 cm horizon

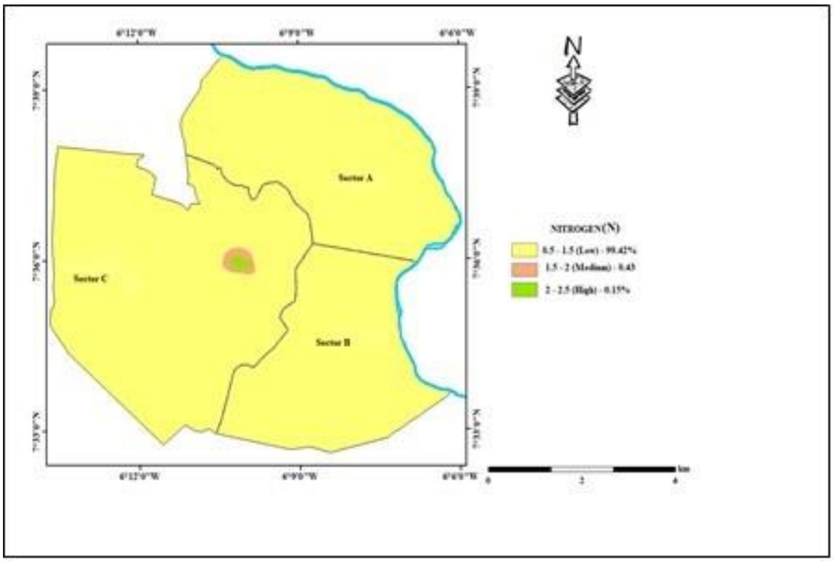

FIGURE 3: Spatial evolution of nitrogen in the 0-40 cm horizon

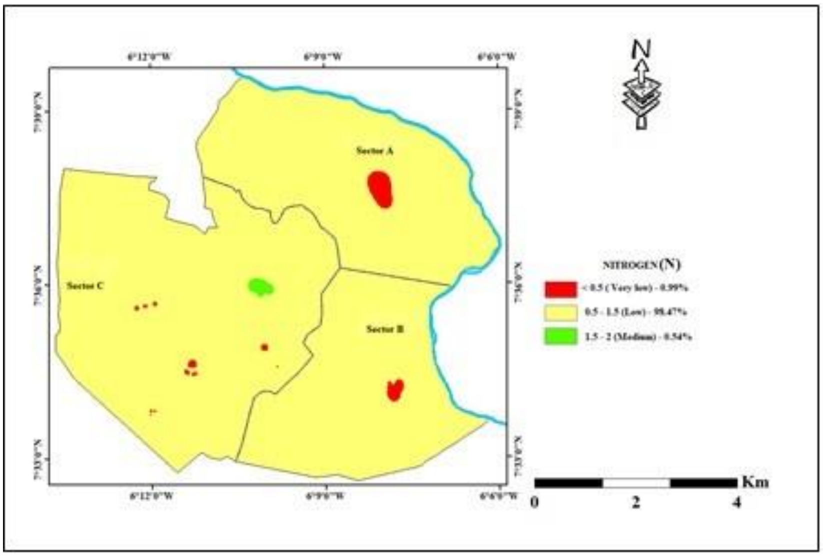

FIGURE 4: Spatial evolution of nitrogen in the 0-60 cm horizon

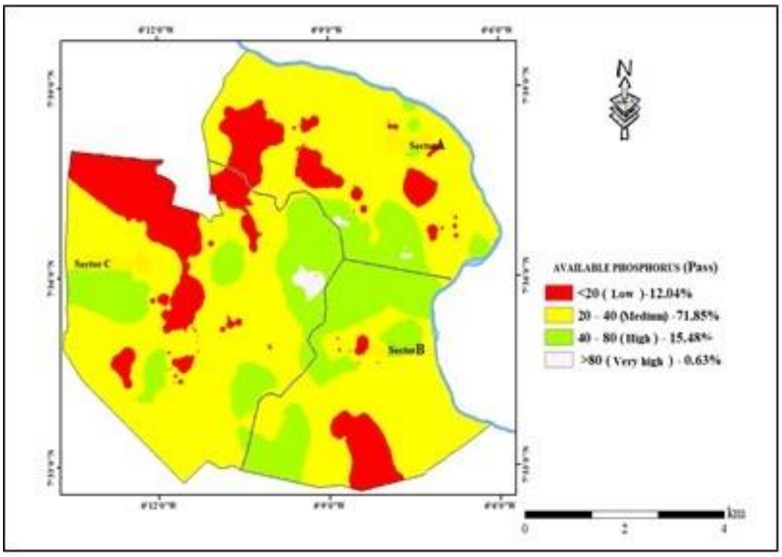

FIGURE 5: Spatial evolution of available phosphorus according to the 0-20 cm horizon

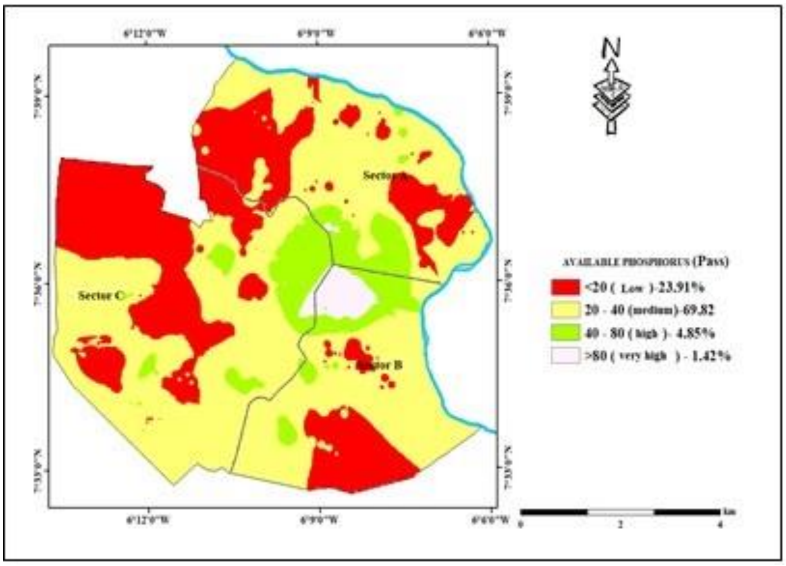

FIGURE 6: Spatial evolution of available phosphorus according to the 0-40 cm horizon

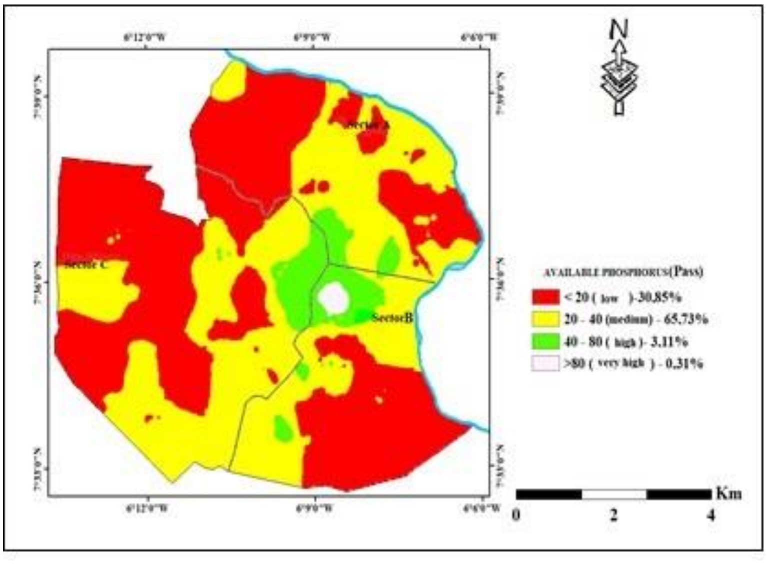

FIGURE 7: Spatial evolution of available phosphorus according to the 0-60 cm horizon

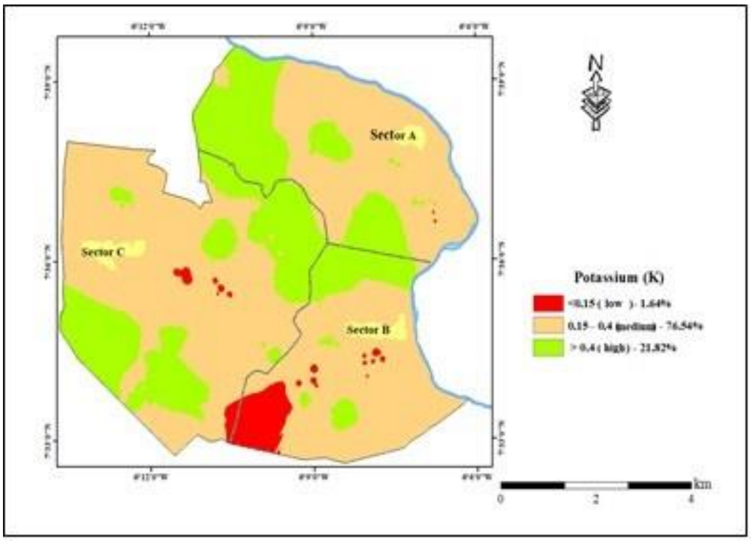

FIGURE 8: Spatial evolution of potassium in relation to the 0-20 cm horizon

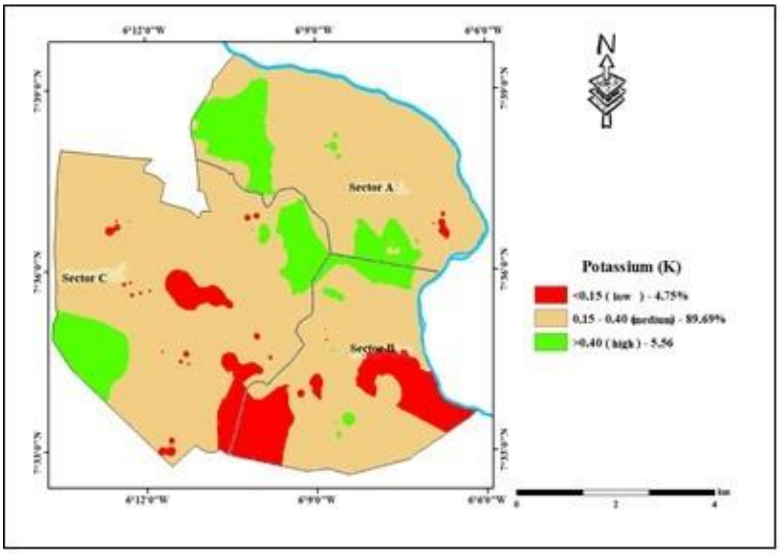

FIGURE 9: Spatial evolution of potassium in relation to the 0-40 cm horizons

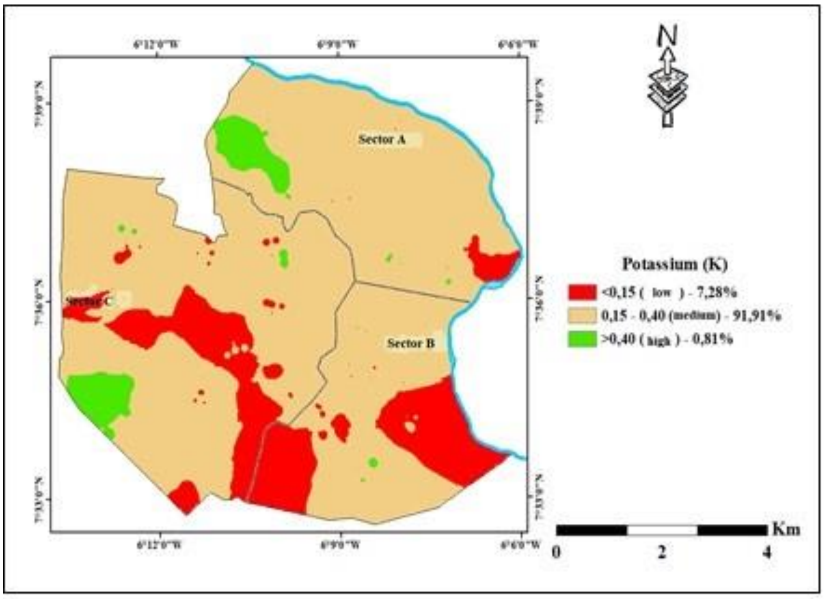

FIGURE 10: Spatial evolution of potassium in relation to the 0-60 cm horizon

IV. DISCUSSION

The granulometry of the soils shows the relative importance of clay, silt and sand content. The texture triangle (GEPPA) (Chevalier, 2001) was used to determine the variation of texture with depth in the study area. Soil texture is an important physical property that controls quality and allows estimation of the soil transfer function (Bouma, 1989) and is useful for example in predicting hydrodynamic properties (FAO, 2007). The surface horizon (0-20 cm) was mainly silty and slightly more abundant than the lower horizons (0-40 and 0-60 cm). According to Malgwi and Abu (2011), fine-textured (loamy) soils often have problems with structure and water infiltration. This would indicate a low level of physical fertility. It was also found that the clay fraction increased with depth. In addition to the soil genetic causes, a deep clay accumulation would be amplified by the continuous irrigation of the sugarcane plots. This could lead to the compaction of deep horizons which is detrimental to soil fertility (Alongo and Kambele, 2013). With a relatively high clay content (20 to 30%), more or less significant retentions of nutrients and water are favored; however, high clay content can result in very poor physical properties, including an impermeable environment, poor aeration of soil stopping harmonious root penetration, soil compactness in dry conditions and high plasticity in wet conditions. This can make tillage difficult. This can imply a medium level of physical fertility, as observed in the work of Zro *et al.* (2012). The proportions of sand in the different horizons is more or less invariable along the profiles. These proportions were above 30% in some cases. These high sand contents could be attributed to the nature of the parental rock. Indeed, the sand in the soils comes from sediment rich in (Deh *et al.*, 2012).

The soils in the study areas are generally slightly acidic (5.0 > pH < 6.5). This demonstrates the impact of continuous cropping on the environmental conditions of the soils. Many authors have reported that low acidic soil pH is not a constraint for sugarcane. because, even though the optimum is pH 7 for the best soils under sugarcane, the plant can grow on acidic (pH = 4.5 - 6) or slightly basic (pH =7.3-7.6) soils (Tossah *et al.*, 2006).

The organic matter level in the soils is good to medium for the horizon 0-20cm (value between 10 and 25 $g.kg^{-1}$). These observed values of organic matter are due to the concentration of agricultural operations, such as the application of crop residues, in the surface horizons. (Bouadou, 2014). As for the low level of organic matter in the 0-40 and 0-60 cm layers (values between 5 and 15 $g.kg^{-1}$ according to the standards of Pouzet *et al.* (1997)). This could be detrimental to the soil fertility (Alongo and Kambele, 2013).

Total nitrogen and total carbon values in soils are generally low according to the standard shown by Pouzet *et al.* (1997). This low value could be attributed to the influence of continuous and intensive cultivation, a common practice in sugarcane (Noma *et al.*, 2011).

The C/N ratio is of great agronomic interest; indeed, it conditions the organic matter mineralisation process. When C/N is less than 9, the mineralisation of organic matter is rapid, which entails a risk of nitrogen loss. When the ratio is between 9 and 12, it is considered to be normal, as is the case the study zone soil. The C/N ratio is also an indicator of biological activity.

Assimilable phosphorus levels are good for the 0-20cm horizon and low for the 0-40 and 40-60cm horizons. These results corroborate those of Lompo *et al.* (2008) who revealed the phosphorus deficiency of soils in sub-saharan West Africa. In general, the levels decrease from the surface to the deeper horizons. The relatively high phosphorus levels at the surface horizon are thought to be due to the high content of organic matter add to the clay content in this horizon of soil (Hinsinger *et al.*, 2017).

The Cation Exchange Capacity (CEC) of the soils are medium (6< CEC < 12 cmol.kg-1) related to the standard indicated by Pouzet *et al.* (1997). And the fact that the CEC value of the 0-20 cm horizon is higher than the global average of the CEC value, and those of the other horizons (0-40 cm and 0-60 cm) are lower than this global average, shows the great capacity of organic matter to contribute to the increase of CEC value, and this more than the clay content. This has also been established through the correlation matrix between physical and chemical parameters by Endamane *et al.* (2021). Moreover, such an evolution also shows the drop in the value of the CEC, from the soil surface horizon to the depth horizons, which would be associated with the concentration gradient of organic matter in the profile (Kouakou, 2017). This would be a reality of tropical soils (Guibert, 1999), where the dominant clay type is kaolinite (Legros, 2013).

The values evolution of Ca^{2+}, K^{+}, Mg^{2+} and saturation rate of the adsorbent complex is approximately similar to this of CEC. This can be due to the proportionalaty between the values of CEC and those of these exchangeable bases (Gnahoua *et al.*, 2008).

Although the value of the Ca/Mg ratio in the soils of the plots of the agroindustrial unit of Zuénoula has an upward trend with increasing soil depth, this ratio would always be within a range of optimal values (1 ,5 to 5) for most annual crops in the tropics, according to Boyer (1982).

As for the Mg/K ratio, evolving on the order of 7 in the superficial horizon, to reach a higher value (10) in a thicker layer (60 cm), it would be acceptable with regard to several observed values and reported by Boyer (1982). However, an increase in this ratio would reflect a relative decrease in the potassium content. Whereas, Buttin and Chabalier (1989) show that potassium would be the most exported element by sugar cane, compared to the nutrition in nitrogen, phosphorus, calcium and magnesium. It is therefore observed that increasingly high values of the Mg/K ratio could reveal an availability of Magnesium (Akpan-Idioc, 2012), but also a potassium deficit.

V. CONCLUSION

After the study related to the mapping of the bioavailability of nutrients in sugar cane cultivation at the Integrated Agricultural Unit of Zuenoula, the results show that the soil texture was loamy over the first 60 centimeters of soil depth. The soils are slightly acidic. Nitrogen levels are low over at least 95% of the site area. The phosphorus content is also low, over about 30% of the extent of the zone. And the potassium content is acceptable over most of the zone. But the decrease with depth of the different contents of these mineral elements requires a special attention to avoid a significant deficit, mainly when the roots of the crop access the deeper layers of the soil.This could be accentuated by certain ratios (Ca/Mg and Mg/K) which point to nutritional imbalances. Knowing the spatial evolution of soil nutrients is important to determine the amount of fertilizer to apply to correct fertility levels and increase production, in order to be able to meet the standards of rational fertilization in sugarcane cultivation.

ACKNOWLEDGEMENTS

The authors would like to thank the General Management of SUCRIVOIRE, the Training and Research Unit of Earth Sciences and Mining Resources of Félix Houphouët-Boigny University of Abidjan-Cocody (Côte d'Ivoire) and the Agronomic Studies Service of Integrated Agricultural Unit of Zuénoula for their support in carrying out this study.

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Assessment of Plastic Waste Generation and Eco-Friendly Management: A Review

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Received:- 02 August 2023/ Revised:- 12 August 2023/ Accepted:- 23 August 2023/ Published: 31-08-2023

Abstract— *Since the invention and inception of plastics in our daily life, the continuous use of the product has increased causing harmful effects to the environment and human life. Now the time has come to awake and be aware of the use and management of plastics in our daily life. The current scenario reveals that plastic consumption has increased in our daily life activities, whether it be food as packaging items, cosmetics, plastic bottles, polythene, and pharmaceutical sector, and other manufacturing and production sectors for efficient and safe delivery of the items. The synthetic plastic production process and degradation of used products, if not managed properly, show adverse impacts on the environment. The reuse and recycling of plastic products seem to be the best strategy, however, depends on the product, technique applied and rate of decomposition. In the present circumstances, the use of bio-plastics is a better alternative, as they are safe, eco-friendly, biodegradable, without harming the living components of any ecosystem. Moreover, the potentiality of microorganisms to degrade the bio-plastic wastes has opened a new forum on reuse, recycling, and processing of plastic waste management. This comprehensive review aims at the generation of plastic waste, their impact on human life and the environment, reducing and recycling techniques, the significance of biodegradable plastics, and their decomposition using microorganisms. Moreover, the problems and challenges that occur during the production and degradation of plastic waste are more important to minimize the impact for sustainable development.*

Keywords*— *Plastic pollution, recycle and reuse, ecofriendly management, microorganisms.

I. INTRODUCTION

Plastic wastes (PW) have emerged as a major problem causing adverse impacts on the environment and human health. Plastic production starting from 1950, about 6.3 BT of plastics produced worldwide up to 2018, however only 9% is recycled and 12% is incinerated (Alabi et al.,2019). Plastic pollution most visible in developing countries, with improper waste collection systems compared to developed nations, remains a troubling process, especially in the collection of discarded plastics (Parker, 2019). Plastics as an integral part of our life appear in various products of daily use, responsible for carbon emission affecting the ecosystem cycle and becoming a great threat to human health (Filiciotto, & Rothenberg, 2021). Plastic waste is responsible for causing an impact on climate change which otherwise affects genes, species and the whole biome (Pandey et al, 2016 a). It was observed that landfill disposal of plastic and incineration process accounts for emissions of CO_2 253 and −673 g kg^{-1} to 4605 g kg^{-1}, respectively (Eriksson and Finnveden 2009). The most damaging impact of PW is on aquatic ecosystems affecting entanglement, ingestion, and blockage of the intestine, and microplastic is even worse causing intrinsic toxicity due to leaching, absorbing contaminants, and pathogens, disturbing chemical interaction in aquatic animals (Amobonye et al, 2021). The plastics with a big carbon footprint metrics should be monitored timely for reducing their impacts on the environment (Pandey et al, 2016 b) Therefore a need for better research on plastic wastes, large-scale clean-up drives, public awareness, and information sharing among decision-makers for fulfilling knowledge gaps should be preferred (Syberg et al 2020).

II. PLASTIC WASTE GENERATION IN INDIA

In the post-independent era, India has witnessed a progressive increase in the production and consumption of plastic. However, the country lacks proper waste collection and segregation technology, therefore the management of discarded plastics waste has become a challenging task (Banerjee et al 2014). In India nearly 9.4 Million tonnes of plastic waste is generated per annum (which amounts to 26,000 tonnes of waste per day), and nearly 5.6 million tonnes of plastic waste is recycled (i.e. 15,600 tonnes of waste per day) whereas 3.8 Million tonnes is left uncollected or littered (9,400 tonnes of waste per day) (UNIDO, 2018). About 60% PW is recycled, which is higher than the global average of 20% (Geyer et al, 2017) but still, over 9,400 tonnes of plastic waste is either landfilled or ends up polluting streams or groundwater resources. Around 25,950 tonnes of plastic waste produced per day, 40% is thrown unattended causing soil and water pollution, affecting drainage and river systems, ingestion by stray animals, and littering of the marine ecosystem (Yadav, 2019). The present clean-up strategies of plastic pollution are not sufficient enough to compete with the increasing volume of plastic entering our ecosystem and require a global multifaceted approach (Prata et al 2019).

III. IMPACT OF PLASTIC WASTE

Plastic waste pollution shows a wider impact on environment diversity, perseverance, raises global issues, and threats to human health and organism. The plastic cycle operating in the atmosphere, aquatic and terrestrial systems is also a matter of serious concern (Li et al 2020). The single-use plastics (SUPs) waste are even more harmful as they are causing a threat to floral growth, soil invertebrates, land animals, birds, and marine lives (Chen et al 2021). The impact of plastic pollution on the soil ecosystem using the earthworm model comes with an outcome that microorganisms, invertebrates, insects, and plants should be experimentally tested to understand the deleterious effect on the whole soil ecosystem (Chae and An 2018). The disposal mechanism of plastic waste creates social and environmental impacts. The used polyethylene terephthalate (PET) plastic bottles should be cent-per-cent disposed and a study reports that 75 % flake production and 25 % landfilling shows the least social impact (Foolmaun and Ramjeeawon 2013). Household and industrial plastic waste mainly contain phthalate contamination in form of DBP (Dibutyl phthalate), DBP (Di-iso-butyl phthalate), and DEHP (Diethylhexyl phthalate). Among these DEHP shows highest frequency hence recycling plastics requires phthalates-sensitive execution (Pivnenko et al 2016).

IV. REDUCING AND RECYCLING PLASTIC WASTE

In order to reduce plastic waste pollution the modulation of production and uses, eco-designing, practice of using recycled plastics, the habit of reduction of the use of plastics, using renewable energy technique for recycling, production house responsibility to manage waste, proper waste collection mechanism, recycling, using biodegradable and bio-based plastics, and advancement in the recycling of e-waste, are some best practices (Prata et al 2019). Recycling by a reduction in material use through product reuse or downgauging, using alternative biodegradable materials, and energy retrieval in form of fuel are some best techniques to get rid of plastic waste (Hopewell et al 2009). The carrying of reusable bottles and bags can help to minimize the plastic footprint. The recycling of polyethylene terephthalate, into useful polyester fabric and automotive parts, is also a good practice (NRDC, 2020). Civil Engineering processes also show the reuse of plastic bottles. The use of fly ash as an infill material in composite cells with optimum height increases the load-carrying potentiality of the cells and can be used as a compression object (Dutta et al 2016). The scientific sterilization and the use of eco-friendly sealed bags like bio-plastics help in the safe disposal of contaminated plastic wastes and also reduce the risk of disease transmission (Vanapalli et al 2021). The degradation of synthetic plastics using bacteria, fungi, certain actinomycetes, algae, and insects should be attempted as they have shown the potential to ingest polymers and convert them into eco-friendly carbon compounds. In order to facilitate and enhance the microbial mechanism scientific techniques like changes in metabolic pathway design, enzymatic characteristics and molecular cloning should be given more priority (Amobonye et al, 2021). The present regulatory instruments like regulations, norms, laws, and recommendations for the reduction of the eco-toxicological impact of plastics in the environment should be properly monitored (da Costa et al 2020).

V. BIODEGRADABLE PLASTICS

The use of biodegradable plastics has emerged as an alternative to synthetic plastics to reduce plastic pollution. Natural plastics are generally made from microorganisms or plant and animal sources. In this process, under favorable fermentation conditions, bacterial strains utilize carbon sources and produce and store bio-plastics. These materials are referred polyhydroxyalkanoates (PHA) and are safe, are without toxic by-products, and are easily degraded by microorganisms (Alshehrei, 2017). The use of biodegradable plastics helps to reduce the problems of microplastics, climate change, and littering. The bio-plastics minimizes the socio-economic and environmental impact of plastics, thus their use, production, and commercialization should be preferred (Filiciotto, & Rothenberg, 2021). Various standardization bodies have introduced scientific and technical standardized techniques and criteria to assess Environmentally degradable polymers and plastics (EDPs), based on some basic characteristics like biodegradability, providing certification to the material (Krzan et al, 2006).

VI. MICROORGANISM INVOLVED IN BIODEGRADATION OF PLASTIC

Plastic degradation is always a serious threat to the environment. The use of microorganisms for plastic degradation is the cheapest and eco-friendly method as it helps to convert the waste into low molecular weight compounds without harming the ecosystem (Fazakat and Hashmi, 2020). Biodegradable plastics are easily assimilated by microorganisms and disappear from our environment. The bioremediation process using microbial enzymatic degradation is safer without waste accumulation. The environmental factors such as thermo-stability, pH, substrate molecular weight and complexity, and the surface erosion of polymer film are some of the important criteria for hydrolytic biopolymer degradation producing monomer of low molecular weight, and also generates methane, carbon dioxide, and water (Roohi et al, 2017). The biodegradation of plastics depends on the physicochemical structure of the used materials, environmental conditions, and the microbial community involved in biodegradation. Some common misconceptions like the gaps among biodegradation levels, between the biodegradation conditions, and between public perception and the actual environmental fate of biodegradable products should be properly addressed and sorted (Choe et al, 2021). The biodegradation kinetics of certain bioplastics like PHBV, PHB, and PCL reveals that poly(3-hydroxybutyrate-co-valerate) (PHBV) and poly(3-hydroxybutyrate) (PHB) degrades anaerobically and aerobically in 77 and 117 days respectively, while Polycaprolactone (PCL) biodegraded aerobically in 177 days. The total biomass growth reported to be 10 to 30.5% of the total initial carbon and the lowest size of the particle that can be used for testing were in the range of 100–250 µm, indicating the significance of bioplastic degradation suitable for standardization in bio-economy in context of plastic waste biodegradation (Garcia-Depraect et al, 2022).

According to research, certain species of bacteria like *Ideonella sakaiensis* that exist during plastic bottle-recycling have the potential to degrade and metabolize plastic and hydrolyze polyethylene terephthalate (PET) (Yoshida et al, 2016). A study reports that caterpillar wax moth larvae *Galleria mellonella* was reported to biodegrade polyethylene (PE), which are largely used in packaging with significant environmental impact, producing ethylene glycol (Bombelli et al, 2017). The soil microbiota plays a significant role in the degradation of bioplastics in soil. The soil bacteria *Pseudomonas chlororaphis* and *Cupriavidus necator* has potentiality in biodegradation and decomposition of bioplastics formulated from Polylactide acid (PLA) in 250 days (Blinkova and Boturova, 2017).

VII. CONCLUSION

In conclusion, plastics have become an integral part of our lives. The use of plastic products that are biodegradable should be preferred over synthetic plastics. The use of landfills, bio-plastic, and degradation of plastics using microorganisms are some better alternatives without any harmful impacts on the environment and human health. The recycling and reuse of bio-plastic are safer from a human health point of view. Moreover, they do not show any harmful impact on air, water, and the land ecosystem.

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Interaction Effect of Sowing Time and Nitrogen Levels on Growth and Yield Parameters on Cauliflower (*Brassica Oleracea* Var. *Botrytis*)

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Received:- 07 August 2023/ Revised:- 15 August 2023/ Accepted:- 14 August 2023/ Published: 31-08-2023

Abstract— *The present investigation entitled Interaction effect of sowing time and nitrogen levels on growth and yield parameters on Cauliflower (Brassica oleracea var. botrytis) was carried out using 10 treatment combinations and was laid out in Factorial Randomized Block Design (FRBD) with three replications. The experiment comprised two main parameters, namely the sowing dates and the nitrogen levels. Sowing Time was 15th September & 20th October while Nitrogen levels were kept 50Kg N/ha, 65Kg N/ha, 100Kg N/ha,125Kg N/h, 150Kg N/ha respectively. Appropriate analysis of variance on the results of each experiment was performed and the data obtained from the field surveys was pooled and then data was analysis with the help of OP STAT software. It could be concluded that the nitrogen level 150kg/ha show maximum result both in growth and yield characters and sowing date 20th October performs well in all parameters. The combined effect of sowing dates and nitrogen levels showed that sowing on 20th October, nitrogen level 125kg/ha performed well in respect of contributing growth characters and yield.*

Keywords— Cauliflower, sowing, nitrogen levels, Randomized Block Design, Curd yield/plot, Leaf Length.

I. INTRODUCTION

Cauliflower (*Brassica oleracea* var. *botrytis*) is a cruciferous vegetable that belongs to the Brassicaceae family, which also includes other vegetables like broccoli, cabbage, and Brussels sprouts. Cauliflower is native to the Mediterranean region and has been cultivated for thousands of years. It has become a popular vegetable worldwide due to its mild flavor and versatility in cooking. Cauliflower is a low-calorie and nutrient-dense vegetable. It's an excellent source of vitamins and minerals, including vitamin C, vitamin K, vitamin B6, folate, and potassium. It also contains dietary fiber and antioxidants. The edible part of cauliflower is known as curd, which consists of a shoot system with short internodes, branches apices and bracts. The edible portion of this vegetable is approximately 45 per cent of the vegetable as purchased. It has high quality of proteins and peculiar in stability of vitamin C after cooking. It is rich in minerals such as potassium, sodium, iron, phosphorus, calcium, magnesium etc. It also contains vitamin A (Nath, 1976) Conew (1959) has made an analysis on fresh weight basis. Cauliflower contains 92.7 per cent water and the food value per 100 g of edible ascorbic acid 70 mg, thiamine 0.2 mg, riboflavin 0.1 mg and niacin 0.57 mg. Sulphur containing compounds viz; hydrogen sulfide methanethiol, ethanethiol, propanethiol and dimethyl sulfide in addition to acetaldehyde and 2- methyl propanol have been identified in cooked cauliflower. It's a well-known fact that a crop when sown at optimum time is able to exploit all the environment factors efficiently in the process of dry matter accumulation. The date of sowing is governed mainly by temperature, sunlight intensity, duration and rainfall. These are the crucial factors that can decide establishment, growth and performance of crop through changing morphological system, physiological functioning and time available for the crop to complete its life cycle. Due to different factors seedling vigour is also affected which motivated researchers to evaluate the various sowing dates for growth and yield parameters of cauliflower. Therefore present study was done to investigate Interaction effect of sowing time and nitrogen levels on growth and yield parameters on Cauliflower (*Brassica oleracea* var. *botrytis*) under different growing conditions.

II. MATERIALS AND METHODS

Current investigation was conducted at Guru Kashi University Research Farm, during 2021-2022 for studying Interaction effect of sowing time and nitrogen levels on growth and yield parameters on Cauliflower (*Brassica oleracea* var. *botrytis*) using different growing conditions to observe the effect on germination and growth parameters of Cauliflower. The experiment was consisted 10 treatment combinations, and was laid out in Factorial Randomized Block Design (FRBD) with three replications. The whole experimental area was divided into three equal blocks. Each block was then further divided into 10 plots. Thus there were 30 (10 × 3) unit plots altogether in the experiment. A distance of 45 cm X 30cm was maintained between row to row and plant to plant within the each plot (180m^2. The blocks were kept to facilitate different intercultural operations. The crop was raised by following the package of practice recommended by PAU, Ludhiana. The experiment comprised two main parameters, namely the sowing dates and the nitrogen levels. Sowing Time was 15th September & 20th October while Nitrogen levels were kept 50Kg N/ha, 65Kg N/ha, 100Kg N/ha,125Kg N/h, 150Kg N/ha respectively. Appropriate analysis of variance on the results of each experiment was performed and the data obtained from the field surveys was pooled and then data was analysis with the help of OP STAT software.

III. OBSERVATION RECORDED

The observations recorded during the course of investigation were Plant height (cm), Number of leaves per plant **(**number of intact leaves was counted for each three plants and mean was calculated), Leaf length (cm) **(**recorded with meter scale from tip of foliage to the end of the leaf),Breadth of leaf (cm), Equatorial diameter (cm),Polar diameter (cm),Number of days taken to harvest, Fresh weight of curd (gm),Curd yield/plot (Kg),Yield (q/ha)(the yield ha-1 was recorded in kilograms and then converted into quintals). The composite soil sample was taken from 0-15 cm depth from three spots of experimental field before planting crop. The sample collected from field was first air dried in the shade and then sieved through 2.0 mm sieve and analyzed for the determination of available nitrogen, phosphorus, potassium, electrical conductivity (EC), organic carbon (OC) and pH of the soil. The soil of field was low in available nitrogen (326.14 kg ha^{-1}), low in phosphorus (6.25 kg ha^{-1}) and medium in potassium (140.7 kg ha^{-1}).

IV. RESULT AND DISCUSSION:

4.1 Plant height (cm):

Plant height significantly affected by interaction of nitrogen levels and sowing time, but maximum plant height (28.69 cm) was recorded from 150 kg N/ha and sowing time **20th October** at par with 125kg N/ha and sowing time **20th October** with plant height (28.10cm). While minimum plant height (12.09 cm) was observed in 50 kg N/ha and sowing time **15th September** was applied. The result is in conformity with the earlier findings of Kumar *et al*. (2002). Meena and Malhotra (2006) also reported that significant variation in plant height, number of branches, number of green leaves and yield of green leaves per plant due to effect of different sowing dates.

TABLE 1:
INTERACTION EFFECT OF SOWING TIME AND NITROGEN LEVELS ON PLANT HEIGHT (Cm) ON CAULIFLOWER

Nitrogen Levels / Sowing Dates	50Kg N/ha	65Kg N/ha	100Kg N/ha	125Kg N/ha	150Kg N/ha	Mean of Sowing Date
15th Sept	12.09	14.097	17.09	19.1	21.087	16.693
20th Oct	22.16	26.16	24.093	28.1	28.69	25.841
Mean of Nitrogen Levels	17.125	20.128	20.592	23.6	24.888	

Factors	C.D.
Factor (Sowing Dates)	0.03
Factor (**Nitrogen Levels**)	0.047
Factor (Sowing Dates X **Nitrogen Levels**)	0.67

4.2 Number of leaves:

The number of leaves 20.37 significantly maximum shown by nitrogen level 150kg N/ha followed by 125 N/ha with 19.30 readings. Lowest number of leaves was noted in 50kg N/ha with 17.30 reading. Significantly maximum number of leaves 20.72

was shown by sowing time **20th Oct**ober and minimum number of leaves was 17.49 cm by sowing time **15th September**. The findings indicated that a warmer temperature encourages more vegetative growth which may be the reason for more leaves in early planting (8th September). The result is in conformity with the earlier findings of Kumar *et al*. (2002).

TABLE 2
INTERACTION EFFECT OF SOWING TIME AND NITROGEN LEVELS ON NUMBER OF LEAVES ON CAULIFLOWER.

Nitrogen Levels / Sowing Dates	50Kg N/ha	65Kg N/ha	100Kg N/ha	125Kg N/ha	150Kg N/ha	Mean of Sowing Date
15th Sept	15.14	17.36	18.14	18.367	18.47	17.495
20th Oct	19.47	20.37	21.25	20.24	22.27	20.72
Mean of Nitrogen Levels	17.305	18.865	19.695	19.303	20.37	

Factors	C.D.
Factor (Sowing Dates)	0.012
Factor (**Nitrogen Levels**)	0.019
Factor (Sowing Dates X **Nitrogen Levels**)	0.027

4.3 Leaf Length (cm):

The highest leaf length (39.31 cm) in nitrogen level 125kg N/ha was produced for the 20th October planting which was statically followed with the leaf length (38.47 cm) in nitrogen level 125kg N/ha was produced for the 20th October sown crop. Lowest leaf length was noted in 50kg N/ha 29.57 cm with the crop sown on 15th September. The leaf length 37.52 cm significantly maximum shown by nitrogen level 100kg N/ha followed by 125 N/ha with leaf length 36.83cm. Lowest number of leaves was noted in 50kg N/ha with 17.30 cm reading. The crop which was sown on 20th October shows significantly maximum 36.50 cm leaf length. Lowest leaf length 32.64cm was noted in 15th September. Kumar *et al*. (2002) also recorded that the vegetative characters such as stalk length and leaf number of cauliflower significantly differ with the changes in planting dates.

TABLE 3
INTERACTION EFFECT OF SOWING TIME AND NITROGEN LEVELS ON LEAF LENGTH (cm) ON CAULIFLOWER

Nitrogen Levels / Sowing Dates	50Kg N/ha	65Kg N/ha	100Kg N/ha	125Kg N/ha	150Kg N/ha	Mean of Sowing Date
15th Sept	29.572	31.47	36.58	34.36	31.247	32.646
20th Oct	31.777	35.38	38.47	39.31	37.577	36.503
Mean of Nitrogen Levels	30.675	33.425	37.525	36.835	34.412	

Factors	C.D.
Factor (Sowing Dates)	0.012
Factor (**Nitrogen Levels**)	0.019
Factor (Sowing Dates X **Nitrogen Levels**)	0.87

4.4 Breadth of leaf (cm):

Breadth of leaf increased significantly due to different planting dates and nitrogen levels. The breadth of leaf 24.08cm significantly maximum shown by nitrogen level 100kg N/ha with sowing date 20th October and followed by 150 N/ha and sowing date 20th October with breadth of leaf 22.84cm. Lowest was noted in 50kg N/ha with crop sown on 15th September with 18.65 cm reading. Significantly maximum breadth of leaf 22.14 cm was recorded in nitrogen level 150kg N/ha and it was followed by 100kg N/ha with 20.96 cm leaf breadth. Lowest leaf breadth 19.48 cm was recorded in nitrogen dose 50kg N/ha. The crop which was sown on 20th October, the significantly maximum leaf breadth 22.67 cm was recorded. Lowest leaf breadth

19.64 cm was noted in 15th September. They recorded wide variation among vegetative growth of the different genotypes of cauliflower (Zaki *et al*., 2012; Meena, 2017).

TABLE 4
INTERACTION EFFECT OF SOWING TIME AND NITROGEN LEVELS ON BREADTH LEAF (cm) ON CAULIFLOWER

Nitrogen Levels / Sowing Dates	50Kg N/ha	65Kg N/ha	100Kg N/ha	125Kg N/ha	150Kg N/ha	Mean of Sowing Date
15th Sept	18.65	17.927	17.837	19.449	21.458	19.064
20th Oct	21.312	21.47	24.087	22.089	22.848	22.361
Mean of Nitrogen Levels	19.481	19.69	20.962	20.76	22.14	

Factors	C.D.
Factor (Sowing Dates)	0.022
Factor (**Nitrogen Levels**)	0.035
Factor (Sowing Dates X **Nitrogen Levels**)	0.049

4.5 Equatorial diameter (cm):

Significantly maximum equatorial diameter 25.86 cm was recorded in nitrogen level 100kg N/ha with sown date 20th October and at par by 150kg N/ha with sown date 20th October with 23.64 cm equatorial diameter. Lowest equatorial diameter 20.50 cm was recorded in 50kg N/ha in crop which was sown on 15th September. Significantly maximum equatorial diameter 24.5 cm was recorded in nitrogen level 100kg N/ha and it was followed by 150kg N/ha with 23.58 cm equatorial diameter. Lowest equatorial diameter 22. 21 cm was recorded in nitrogen dose 50kg N/ha. The crop which was sown on 20th October, the significantly maximum equatorial diameter 23. 26 cm was recorded. Smallest equatorial diameter 22.17 cm was noted on 15th September.

TABLE 5
INTERACTION EFFECT OF SOWING TIME AND NITROGEN LEVELS ON EQUATORIAL DIAMETER (cm) ON CAULIFLOWER.

Nitrogen Levels / Sowing Dates	50Kg N/ha	65Kg N/ha	100Kg N/ha	125Kg N/ha	150Kg N/ha	Mean of Sowing Date
15th Sept	20.503	20.411	23.18	23.267	23.53	22.178
20th Oct	23.92	20.366	25.862	22.509	23.641	23.26
Mean of Nitrogen Levels	22.212	20.388	24.521	22.888	23.586	

Factors	C.D.
Factor (Sowing Dates)	0.168
Factor (**Nitrogen Levels**)	0.265
Factor (Sowing Dates X **Nitrogen Levels**)	2.375

4.6 Polar diameter (cm):

Polar diameter were markedly enhanced by sowing seeds on mid-season date (20th October) in comparison with the early sowing crop (15th September). In the mid season sowing date polar diameter was 15.57 cm on 20th October. Smallest polar diameter was noted on 15th September 14.85 cm.

TABLE 6
INTERACTION EFFECT OF SOWING TIME AND NITROGEN LEVELS ON POLAR DIAMETER (cm) ON CAULIFLOWER

Nitrogen Levels / Sowing Dates	50Kg N/ha	65Kg N/ha	100Kg N/ha	125Kg N/ha	150Kg N/ha	Mean of Sowing Date
15th Sept	13.43	14.27	16.57	15.543	14.47	14.857
20th Oct	15.17	16.26	14.24	17.36	14.837	15.573
Mean of Nitrogen Levels	14.3	15.265	15.405	16.452	14.653	

Factors	C.D.
Factor (Sowing Dates)	0.014
Factor (**Nitrogen Levels**)	0.023
Factor (Sowing Dates X **Nitrogen Levels**)	0.92

4.7 Mean Days to Harvest (Days):

The days taken to harvest of cauliflower as affected by different nitrogen and sowing dates. The analysis of variance suggested significant impact of nitrogen and sowing dates application on the number of days taken to harvest of cauliflower heads.

TABLE 7
INTERACTION EFFECT OF SOWING TIME AND NITROGEN LEVELS ON MEAN DAYS TO HARVEST (Days) ON CAULIFLOWER.

Nitrogen Levels / Sowing Dates	50Kg N/ha	65Kg N/ha	100Kg N/ha	125Kg N/ha	150Kg N/ha	Mean of Sowing Date
15th Sept	21.23	18.93	17.85	22.307	22.45	19.83
20th Oct	24	21.463	21.833	19.467	22.307	21.81
Mean of Nitrogen Levels	22.61	20.19	19.84	20.18	22.75	

Factors	C.D.
Factor (Sowing Dates)	0.03
Factor (**Nitrogen Levels**)	0.05
Factor (Sowing Dates X **Nitrogen Levels**)	0.15

4.8 Fresh weight of curd (gm):

Fresh weight of cauliflower head without folded leaves as affected by different nitrogen and sowing dates was weighed. The analysis of variance depicted significant ($P<0.05$) effect of varying nitrogen and sowing dates on the weight of cauliflower head without folded leaves.

TABLE 8
INTERACTION EFFECT OF SOWING TIME AND NITROGEN LEVELS ON FRESH WEIGHT OF CURD (gm) ON CAULIFLOWER

Nitrogen Levels / Sowing Dates	50Kg N/ha	65Kg N/ha	100Kg N/ha	125Kg N/ha	150Kg N/ha	Mean of Sowing Date
15th Sept	635.373	660.093	701.097	730.107	760.12	697.358
20th Oct	780.13	812.097	800.16	820.38	819.28	806.409
Mean of Nitrogen Levels	707.752	736.04	750.628	775.243	786.2	

Factors	C.D.
Factor (Sowing Dates)	0.521
Factor (**Nitrogen Levels**)	0.824
Factor (Sowing Dates X **Nitrogen Levels**)	1.166

4.9 Curd yield/plot (Kg):

The perusal of data indicated that all the treatment increased the curd yield/plot (Kg). Significantly maximum curd yield/plot 36.66 kg was recorded in nitrogen level 125kg N/ha with sown date 20th October and at par by 150 kg N/ha with sown date 20th October with 35.73kg curd yield/plot. Lowest curd yield/plot 27.08 recorded in 50kg N/ha in crop which was sown on 15th September. Significantly maximum curd yield/plot 34.44kg was recorded in nitrogen level 150kg N/ha and it was followed by 125kg N/ha with 34.38kg curd yield/plot. Lowest curd yield/plot 30.60kg was recorded in nitrogen dose 50kg N/ha. Curd yield/plot were markedly enhanced by sowing seeds on mid-season date (20th October) in comparison with the early sowing crop (15th September).

TABLE 9
INTERACTION EFFECT OF SOWING TIME AND NITROGEN LEVELS ON CURD YIELD/PLOT (Kg) ON CAULIFLOWER

Nitrogen Levels / Sowing Dates	50Kg N/ha	65Kg N/ha	100Kg N/ha	125Kg N/ha	150Kg N/ha	Mean of Sowing Date
15th Sept	27.087	29.097	30.23	32.117	33.153	30.337
20th Oct	34.13	35.533	35.22	36.667	35.73	35.456
Mean of Nitrogen Levels	30.608	32.815	32.725	34.382	34.442	

Factors	C.D.
Factor (Sowing Dates)	0.047
Factor (**Nitrogen Levels**)	0.075
Factor (Sowing Dates X **Nitrogen Levels**)	1.206

4.10 Total Yield (q/ha):

Data indicated that all the treatment increased the total yield (q/ha). Significantly maximum total yield 600.10 (q/ha) was recorded in nitrogen level 125kg N/ha with sown date 20th October and at par by 150 kg N/ha with sown date 20th October with total yield 599.38 (q/ha). Lowest total yield 469.17 (q/ha) recorded in 50kg N/ha in crop which was sown on 15th September.

TABLE 10
INTERACTION EFFECT OF SOWING TIME AND NITROGEN LEVELS ON YIELD (q/ha) ON CAULIFLOWER.

Nitrogen Levels / Sowing Dates	50Kg N/ha	65Kg N/ha	100Kg N/ha	125Kg N/ha	150Kg N/ha	Mean of Sowing Date
15th Sept	469.173	488.24	518.187	540.14	562.25	515.598
20th Oct	577.233	595.213	592.27	600.107	599.385	592.842
Mean of Nitrogen Levels	523.203	541.227	555.228	570.123	580.818	

Factors	C.D.
Factor (Sowing Dates)	0.224
Factor (**Nitrogen Levels**)	0.354
Factor (Sowing Dates X **Nitrogen Levels**)	2.501

V. CONCLUSION

It could be concluded that the nitrogen level 150kg/ha show maximum result both in growth and yield characters and sowing date 20th October performs well in all parameters. The combined effect of sowing dates and nitrogen levels showed that sowing on 20th October, nitrogen level 125kg/ha performed well in respect of contributing growth characters and yield.

ACKNOWLEDGEMENT

The authors acknowledge Dr. Navdeep Brar (Major advisor) and Dr. Diljeet Singh, HOD, College of Agriculture, Guru Kashi University, Talwandi Sabo, Bathinda for the facilities provided to carry out this work

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Insecticide Toxicity in Paddy Agroecosystems, Impacts on Soil Health, and Microbial Bioremediation Strategies: A Review

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Received:- 08 August 2023/ Revised:- 13 August 2023/ Accepted:- 21 August 2023/ Published: 31-08-2023

Abstract— *Paddy (Oryza sativa) rice cultivation in India extensively employs chemical insecticides to manage insect pests such as stem borers, leaf folders, and planthoppers. While effective in controlling pests, several commonly used active ingredients, including fipronil, chlorantraniliprole, lambda-cyhalothrin, and thiamethoxam, exhibit persistence in soil ecosystems and pose toxicity risks. This review synthesizes current knowledge on the types of insecticides used, their persistence and toxicological profiles, effects on soil microbial communities critical for fertility, and potential risks to human health. Furthermore, it evaluates microbial bioremediation as a promising strategy to mitigate pesticide residues and restore soil health. In view of the above, sustainable pesticide management practices integrated with bioremediation approaches are needed to balance crop protection and ecosystem health.*

Keywords— Oryza sativa, chemical insecticides, toxicity, soil fertility, microbial bioremediation, integrated pest management.

I. INTRODUCTION

Rice (Oryza sativa), a staple for over half the world's population, is predominantly grown in flooded paddy fields, covering approximately 167 million hectares globally. In India, rice serves as a cornerstone staple crop, playing a pivotal role in national food security and rural livelihoods. Persistent threats from pests, including the rice stem borer, leaf folder, brown plant hopper (BPH), and green leaf hopper (GLH), undermine yields and necessitate robust control measures (Litsinger et al., 2009). Farmers apply an estimated 2–3.5 million tonnes of pesticides annually, with insecticides comprising 61%, herbicides 22%, and fungicides 11% of usage (Aktar et al., 2009). Common contaminants in paddy fields include organophosphates (e.g., chlorpyrifos, malathion), carbamates (e.g., carbofuran), organochlorines (e.g., endosulfan, DDT), triazines (e.g., atrazine), and pyrethroids. These persist due to high organic matter and anaerobic conditions in flooded soils, leading to bioaccumulation in rice grains and runoff into waterways (John & Prakash, 2002).

Chemical insecticides, featuring active ingredients such as fipronil, chlorantraniliprole, lambda-cyhalothrin, and thiamethoxam, have become integral to pest management protocols. Despite their efficacy, evidence highlights their environmental persistence and ecological toxicity, particularly disrupting soil health and non-target biota (DeLorenzo et al., 2001). Risks to human health arise from occupational exposure and dietary residues in harvested rice, with impacts ranging from neurotoxicity and endocrine disruption to millions of pesticide-related deaths since 1960, disproportionately affecting rural Asia (Kumar, 2017). Environmental degradation includes reduced soil microbial diversity and biodiversity loss, as pesticides inhibit bacterial abundance in irrigated rice fields (Gupta et al., 2022). Traditional remediation methods (e.g., incineration, chemical oxidation) are costly and generate secondary pollutants, whereas microbial bioremediation—using indigenous or augmented microbes—degrades xenobiotics via enzymatic pathways, offering substantial cost savings and eco-compatibility (Bhagawati et al., 2020).

1.1 Objectives and Scope of this Review:

This narrative review aims to: (1) synthesize contemporary evidence on the persistence and toxicity profiles of major insecticides used in Indian paddy fields; (2) critically analyze their cascading effects on soil microbial communities and related fertility functions; and (3) evaluate the current state, practical challenges, and future potential of microbial bioremediation as a restorative strategy within this specific agroecosystem.

II. COMMON INSECTICIDES IN INDIAN RICE FIELDS

Major insecticidal active ingredients include fipronil (a phenylpyrazole), chlorantraniliprole (an anthranilic diamide), lambda-cyhalothrin (a synthetic pyrethroid), and thiamethoxam (a neonicotinoid). These compounds target various pests through systemic or contact action and are marketed under brands such as Monil GR (fipronil), Vesticor (chlorantraniliprole), Xylo 5 (lambda-cyhalothrin), and Spora (thiamethoxam). Their widespread use reflects efficacy but necessitates careful management to avoid adverse effects (Prakash et al., 2014).

The common chemical pesticides and herbicides used in rice/paddy fields across India, including active compounds and popular brand names are listed as below (Table 1-3). A notable trend is the reliance on systemic neonicotinoids (e.g., thiamethoxam) for sap-sucking pests like BPH and GLH, while newer chemistry like diamides (chlorantraniliprole) and phenylpyrazoles (fipronil) target lepidopteran borers. The market is served by both multinational and domestic agrochemical companies.

TABLE 1
INSECTICIDES FOR CONTROLLING MAJOR PESTS LIKE STEM BORER, LEAF FOLDER, BROWN PLANT HOPPER

Pest	Active Compound(s)	Brand Name (Trade Name)	Company
Stem borer	Fipronil 0.3% GR	Monil GR	Atul Crop Care
	Flubendiamide 480SC	Fame	Bayer Crop Science
	Chlorantraniliprol 18.5% SC	Vesticor	BASF India Ltd
Leaf folder	Thiamethoxam 25% WG	Spora	Atul Crop Care
	Lambda Cyhalothrin 5% EC	Xylo 5	Atul Crop Care
Brown Plant Hopper	Thiamethoxam 30% FS	Spora Super	Atul Crop Care
	Dinotefuran 20% SG	Token	Indofil India Ltd
	Pymetrozine 50% WG	Chess	Syngenta
	Triflumezopyrim 10% SC	Pexalon	Corteva/DuPont
Green Leaf Hopper	Thiamethoxam 30% FS	Spora Super	Atul Crop Care
Thrips, Gall midge	Spinetoram 11.7% SC	Summit (Delegate)	Dow Agrosciences
	Buprofezin 25% SC	Applaud	Tata Rallis, Orion
	Acetamiprid 20% SP	Manik	Tata

TABLE 2
FUNGICIDES FOR DISEASES LIKE BLAST, SHEATH BLIGHT, FALSE SMUT

Disease	Active Compound(s)	Brand Name (Trade Name)	Company
Blast	Isoprothiolane 40% EC	Rhizo, Fujione	Atul Crop Care, Rallis
	Tebuconazole 50% + Trifloxystrobin 25% WG	Nativo	Bayer Crop Science
	Zineb 68% + Hexaconazole 4% WP	Avtar	Indofil Industries Ltd
Sheath blight	Picoxystrobin 7% + Propiconazole 12% SC	Galileo Way	Corteva Agriscience
False Smut	Copper Hydroxide 77% WP	Blue Shield	Bayer

TABLE 3
HERBICIDES FOR CONTROLLING WEEDS INCLUDING GRASSES, SEDGES, BROADLEAF WEEDS

Weed Type	Active Compound(s)	Brand Name (Trade Name)	Company
Grasses, broadleaf weeds	Bispyribac Sodium 10% SC	Nominee Gold	PI Industries
Annual grasses, broadleaf	Pendimethalin 30% EC	Panida	Tata Rallis India
Various weeds	Pretilachlor 50% EC	Rifit	Syngenta
Grassy weeds	Pyrazosulfuron 0.15% + Pretilachlor 6% GR	Eros Gold	UPL
Target grassy weeds	Cyhalofop-Butyl 5.1% + Penoxsulam 1.02% OD	Vivaya	Corteva

III. PERSISTENCE AND TOXICITY IN SOIL ECOSYSTEMS

Fipronil is highly persistent, with a soil half-life ranging from weeks to months, leading to accumulation risks that threaten soil microbial communities responsible for nutrient cycling and organic matter breakdown (Sundaram & Sundaram, 1996). Its toxicity to beneficial soil microbes and arthropods disrupts soil biological activity, potentially diminishing soil fertility (Meena & Meena, 2021). Lambda-cyhalothrin, another persistent insecticide, is highly toxic to non-target soil organisms, including earthworms and microbial populations, impairing soil structure and function (Cycoń et al., 2022). Chlorantraniliprole and thiamethoxam, though moderately persistent, affect soil microbial diversity and functionality, raising concerns for long-term sustainability (John et al., 2001). Declining microbial biodiversity slows nitrogen fixation and organic matter decomposition, both essential for maintaining soil fertility and crop productivity (Johnsen et al., 2001).

Chemical insecticides and herbicides exert significant negative effects on soil microbial ecology, disrupting community structure, diversity, and functions such as nutrient cycling and organic matter decomposition (Gupta et al., 2022). Herbicides like glyphosate and 2,4-D inhibit nitrogen-fixing bacteria (e.g., Azotobacter and Rhizobium) and nitrifying microbes (Nitrosomonas, Nitrobacter), reducing biological nitrogen fixation, ammonification, and nitrification rates, which impairs soil fertility and nutrient availability (Aktar et al., 2009). Insecticides, such as chlorpyrifos and carbofuran, exhibit variable effects; some show no significant broad impacts on microbial abundance or diversity, while others suppress bacterial and fungal populations at high doses, altering dehydrogenase and phosphatase activities critical for carbon and phosphorus cycling (Kadyan & Chawla, 2020). This variability is often mediated by soil properties like texture, pH, and organic matter content (Gani, 2022). Overall, these pesticides reduce microbial biomass and biodiversity, with persistence influenced by soil properties, potentially exacerbating ecosystem imbalances and long-term soil degradation. Herbicide-induced microbiome shifts can cascade to affect plant health and trophic interactions, underscoring the need for sustainable alternatives to mitigate these ecological consequences (Ruuskanen et al., 2023; Boudh & Singh, 2016).

3.1 Effects on Microbiota and Plant Growth:

At recommended dosages, most insecticides are safe for crops; however, overdose or improper application of persistent insecticides such as fipronil and lambda-cyhalothrin may cause phytotoxic symptoms, including stunted growth, leaf yellowing, and reduced tillering (DeLorenzo et al., 2001). Chemical insecticides and herbicides exert significant and often detrimental effects on soil microbial ecology, impacting community structure, diversity, and crucial ecosystem functions. Soil microorganisms, including bacteria and fungi, are fundamental to soil health, playing vital roles in nutrient cycling (e.g., nitrogen fixation, phosphorus solubilization), organic matter decomposition, and maintaining soil fertility (Jaiswal et al., 2022). The application of various pesticides can lead to reductions in microbial biodiversity, hindering essential ecosystem services (Sharma & Sharma, 2021). For instance, persistent insecticides like fipronil and lambda-cyhalothrin pose accumulation risks detrimental to beneficial soil microbes and arthropods, disrupting biological activities and potentially diminishing soil fertility (Pathak et al., 2020). Such insecticides can reduce soil macro-organism activity, growth, and reproduction, ultimately increasing mortality (Srivastav, 2021). Even moderately persistent insecticides like chlorantraniliprole and thiamethoxam affect soil microbial diversity and functionality, raising concerns for long-term sustainability in agricultural fields (Bhagawati et al., 2020).

Herbicides, while targeting unwanted plants, can inadvertently harm non-target soil microorganisms, altering community composition and metabolic functions, including carbon cycling-related enzymatic activities such as α-1,4-glucosidase, β-1,4-glucosidase, and β-D-cellobiohydrolase (Drigo et al., 2022). Impacts vary depending on the pesticide, concentration, soil type, and existing microbial communities (John & Shah, 2018). For example, studies comparing commercial pesticides have found variable effects on soil carbon microbial functions and community composition, with some showing impacts even at recommended doses (Drigo et al., 2022).

Furthermore, fertilization practices can modify the non-target effects of pesticides on soil microbial communities (Muñoz-Leoz et al., 2012). Combined applications of pesticides and fertilizers lead to complex interactions that influence microbial responses, sometimes exacerbating or mitigating negative impacts.

In conclusion, the widespread use of chemical insecticides and herbicides in intensive farming necessitates a deeper understanding of their interactions with soil microbial communities, with profound implications for soil fertility, plant health, and ecosystem stability. Sustainable pesticide management is essential to mitigate adverse ecological impacts (Ewere et al., 2024).

3.2 Human Health Concerns:

Exposure to these insecticides occurs primarily through occupational contact during application and food residues (Bhoi et al., 2022). Fipronil exposure can induce acute symptoms such as headaches, dizziness, nausea, and, in severe cases, seizures, as it acts on insect and mammalian nervous systems (Jolodar et al., 2016). Lambda-cyhalothrin can cause skin irritation, respiratory distress, and neurotoxic effects due to its action on sodium channels in nerve cells (Upadhayay et al., 2015). Thiamethoxam and chlorantraniliprole exhibit moderate acute toxicity but pose risks of chronic neurotoxicity and reproductive effects with prolonged exposure (Kumar, 2017). Proper personal protective equipment (PPE) use and adherence to residue limits in food products are essential to reduce health risks (Balasangu, 2021).

IV. SUSTAINABLE PEST MANAGEMENT AND RECOMMENDATIONS

Given the environmental and health risks associated with persistent and toxic insecticides, integrated pest management (IPM) practices emphasizing minimal chemical use, biological control agents, and crop rotation are imperative (Prakash et al., 2014; Singh & Gupta, 2016). Adoption of safer alternatives and precise application techniques can reduce pesticide loads in soil and minimize exposure risks (Sehgal et al., 2021). Continuous monitoring of soil health and pesticide residues supports sustainable rice production and protects ecosystem integrity (Singh & Jasrotia, 2021; Elakkiya & Sujeetha, 2017).

4.1 Microbial Bioremediation:

Microbial bioremediation harnesses the metabolic properties of microbes and their catabolic enzymes to mineralize xenobiotics into CO_2, H_2O, and non-toxic byproducts via mineralization, co-metabolism, or cometabolism with carbon sources such as glucose (Pathak et al., 2020). Core pathways include hydrolysis by organophosphorus hydrolase (OPH), which cleaves P-O bonds in chlorpyrifos to yield 3,5,6-trichloro-2-pyridinol (TCP) subsequently oxidized by dioxygenases; oxidation through cytochrome P450 monooxygenases hydroxylating imidacloprid to olefin and 5-hydroxy metabolites; reductive dehalogenation of endosulfan to dieldrin mediated by glutathione S-transferases; and fungal conjugation via lignin peroxidases in species like Phanerochaete chrysosporium for pyrethroid ring cleavage (Sharma & Sharma, 2021). In anaerobic paddy soils, sulfate-reducing bacteria drive organochlorine reduction, while flooding induces desorption to improve bioavailability (Jaiswal et al., 2022). Remediation strategies encompass bioaugmentation (e.g., inoculating 10^4 cells g^{-1} soil with degraders), biostimulation using amendments like biochar to enhance native populations, and rhizoremediation leveraging rice root exudates to activate consortia, collectively reducing pesticide half-lives by 50–80% (Bhagawati et al., 2020).

Bacteria predominate due to rapid proliferation, with consortia surpassing monocultures by 20–30% through synergistic interactions (Srivastav, 2021). Notable examples are summarized in Table 4. Fungi such as Phanerochaete chrysosporium degrade 91% of endosulfan-chlorpyrifos mixtures without peroxidase induction and synergize with mycorrhizae (Glomus spp.) for phoxim remediation in rice-analogous systems, whereas Trametes versicolor eliminates cypermethrin using laccases in herbicide-insecticide blends (Bharadwaj et al., 2019; Sharma et al., 2016). Algal contributors like Chlorella vulgaris and Scenedesmus quadricauda, sourced from paddy effluents, biosorb propanil and degrade dimethomorph at 40 µg L^{-1}; cyanobacteria such as Anabaena sequester up to 6779 ppm chlorpyrifos in bioreactors (Gomes et al., 2022).

TABLE 4
EXAMPLES OF MICROORGANISMS DEMONSTRATED TO DEGRADE PESTICIDES IN PADDY-RELEVANT CONTEXTS

Microorganism	Pesticide Degraded	Key Mechanism/Enzyme	Efficiency / Notable Finding	Reference
Ochrobactrum sp. JAS2	Chlorpyrifos	Organophosphorus hydrolase (OPH)	Degraded 300 mg L^{-1} in 12h; reduced soil half-life from 40.8 to 18.7 days. Also promotes plant growth via IAA production.	Jaiswal et al., 2016
Burkholderia cepacia PCL3	Carbofuran	Carbofuran hydrolase	Shortened half-life to 3.62 days (alone) or 1.60 days (in consortia) in flooded soils.	Odukkathil & Vasudevan, 2012
Phanerochaete chrysosporium (Fungus)	Endosulfan, Chlorpyrifos	Lignin peroxidases, non-specific oxidation	Degraded 91% of pesticide mixtures without enzyme induction.	Bharadwaj et al., 2019
Consortium of native soil microbes	Various	Synergistic metabolic pathways	Performance exceeds monocultures by 20-30% in degradation rates.	Srivastav, 2021

V. CHALLENGES AND LIMITATIONS

Despite these efficacies, challenges include sorption-induced low bioavailability (elevated K_d for chlorpyrifos), ageing residues retaining 10% persistence, and abiotic optima (pH 6–8, 15–35°C) beyond which degradation ceases (<5°C) (Boudh & Singh, 2016). Paddy-specific issues include flooding-imposed oxygen deficits impeding aerobes, competitive exclusion of inocula by natives, toxic byproducts like TCP, and GMO regulatory impediments, exacerbated by herbicides curbing rice field microbial diversity by 20–50%. A significant challenge remains scaling successful lab and pot trials to consistent field-level efficacy under variable environmental conditions. Pesticide applications further disrupt community structures, diminishing eco-multifunctionality (Padmavathi, 2015).

VI. SUMMARY & CONCLUSIONS

Chemical insecticides play a critical role in safeguarding Indian rice crops; however, their persistence and toxicity challenge soil microbial health, plant growth, and human safety (Bhoi et al., 2022). Balancing effective pest control with environmental stewardship requires informed pesticide use, promotion of IPM, and enhanced regulatory oversight (Dhandapani, 2018). Future research to understand long-term impacts and develop safer practices is key to sustainable rice agriculture (Pathak & Shakywar, 2015).

VII. RECOMMENDATIONS

To harmonize pest control with sustainability in Indian rice cultivation, a multi-stakeholder approach is recommended:

- **For Researchers:** Prioritize development of efficient microbial consortia over single strains, conduct long-term field validations of bioremediation strategies, and investigate the combined effects of pesticide mixtures on soil microbiomes under realistic paddy conditions.
- **For Farmers, Agronomists, and Extension Services:** Actively adopt IPM frameworks incorporating biological control agents (e.g., *Trichogramma japonicum*), cultural practices like crop rotation, and promote the use of biofertilizers (e.g., *Azolla*) to reduce chemical reliance. Training must emphasize safe handling, precise dosing, and proper PPE use.
- **For Policymakers and Regulators:** Strengthen enforcement of Maximum Residue Limits (MRLs) in food and promote routine environmental monitoring. Support policies that incentivize soil health initiatives (e.g., organic

amendments, cover cropping) and fund farmer education programs. Public awareness campaigns can drive consumer demand for sustainably produced rice.

Microbial bioremediation, integrated within a robust IPM strategy, offers a promising pathway to detoxify contaminated paddy soils, restore microbial balance, and ensure the long-term productivity and ecological health of this vital agroecosystem.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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