International Journal of Scientific Research and Modern Technology (IJSRMT) ijsrmt.com
Volume 4, Issue 7, 2025
DOI: https://doi.org/10.38124/ijsrmt.v4i7.653

Assessment of Polymer-Coated Fertilizers on Maize Quality and Functionality Through Life Cycle Analysis

Faseeha Muqadus[1]; Sameen Fatima[2]; Khadija Mushtaq[3]; Andleeb Zahra[4] ;Muhammad Abdul Rehman Shahid[5]

[1,2,3,5]Research Assistant; [4]Assistant Food Safety Officer

[1]National Institute of Food Science and Technology, University of Agriculture, Faisalabad, Pakistan;
[2]Environmental Science, University of Agriculture, Faisalabad, Pakistan;
[3,4]Institute of food Science and Nutrition, BZU, Multan, Pakistan;
[5]Food Science and Technology, The Islamia University of Bahawalpur, Punjab, Pakistan

Publication 2025/07/29

Abstract

The growing need to develop and use sustainable agricultural practices has increased the importance of the development and usage of controlled-release fertilizers, so-called polymer-coated fertilizers. This paper examines the effect of polymer coated fertilizer on yield quality, functional properties, and maize growth in addition to assessing its life cycle performance on the environment. An experiment was carried out in the field of uncoated conventional fertilizer and some polymer coated fertilizers treatments. The principal quality factors of maize harvested, such as protein content, state of moisture, starch profile, and the wholeness of the kernels were identified and statistically analyzed. Their functional parameters including water absorption index, gelatinization behavior and thermal stability were also ascertained to know whether there is a possibility of using the maize in the food processing and production industries. The life cycle analysis took into account the whole production process the pathway starting with fertilizers to end with the product after the harvest, with respect to greenhouse gases emission, consumption of energy, water footprint, and ecotoxicity. The findings further indicated that nutrient use efficiency of polymer-coated fertilizer significantly enhanced and held the nutrient loss by means of leaching, which enhanced the quality of maize and its useful properties. Also, the LCA indicated that even though the initial energy is used in excess in production of polymer-coated fertilizers owing to coating methods, the total environmental cost becomes lower owing to less frequent application and better crop yield. The combined evaluation gives an idea about the agronomic and environmental benefit of polymer-coated fertilizer use in maize production. The results confirm the opportunity of such fertilizers to increase food quality and reduce the ecological consequences supporting a more sustainable and effective agriculture system.

***Keywords**: Polymer-Coated Fertilizers, Maize Quality, Functional Properties, Life cycle Analysis, Sustainable agriculture, Nutrient Efficiency.*

I. INTRODUCTION

The agricultural intensification that has been desired all across the globe resulted in a massive reliance on synthetic fertilizers in order to increase the production and farming capacity in food production. Nonetheless, the nutrient use efficiency of conventional fertilizers, in particular, the nitrogen-based formulas, is usually low, thus leading to serious environmental problems such as greenhouse gas emissions, eutrophication, and soil degradation (Ciampitti & Vyn, 2014; Zingore et al., 2022). Most of the problems with nutrient intake by crops including maize lead to economic and ecological pressures, and new fertilizer strategies should be designed so that they do not violate the concept of sustainable agriculture (Velten et al., 2015; Lal, 2008). Among the promising directions developed in recent decades, it is possible to point to the use of polymer-coated fertilizers (PCFs) that are intended to deliver all the necessary nutrients in a controlled and gradual way, being coordinated with the rate of nutrient uptake by the crops. Confinement of nutrients on a non-permeable capsule that is semi-permeable polymer helps to curtail the problem of rapid dissolution and leaching and consequently retention of nutrients by the soil and increased plant uptake (Shaviv et al., 2003; Du et al., 2006). Research indicated that, these coatings commonly developed using biodegradable or inert polymers have the ability to enhance root growth and nutrient retention and generate optimal plant metabolic activities (Kassem et al., 2024; Adams et al., 2013).

In the growth of maize, nutrient technology is very important not only to increase production but also to define grain quality and functional properties (such as protein content, amino acid balance, starch profile, and antioxidant capacity). Especially, with the introduction of Quality Protein Maize (QPM), the focus has changed not only on the quantity of yield but also on the quality of the maize grain, both bio-wise and nutritionally (Vasal, 2000; Prasanna et al., 2001). Usually, the various traditional techniques of fertilization do not successfully address the specific need in nutrients that should facilitate the preservation of these high-grade qualities, especially at the key points of phenological development of maize (Gibbon & Larkins, 2005; Ghaffari et al., 2011). Although there are agronomic advantages of PCFs, little research has been done on the overall environmental consequences of PCF production, use and disposed-of effects. Their real sustainability potential should be gauged not only by the performance of the crop but also by its impact on life cycle environmental foot print of these fertilizers under field conditions in reality. Life Cycle Assessment (LCA) provides a competent methodological framework in order to measure these impacts on a cradle to grave basis. It allows evaluating resource consumption, emissions and possible ecological outcomes throughout the whole fertilizer maize production chain (Boone et al., 2016; Supasri et al., 2020).

Several LCA analyses have been carried out on assessing maize production systems across different agroecological regions and all of them demonstrate that fertilizer application imposes an uneven burden to the environment in the form of nitrous oxide, fossil fuel and nutrient loss (Grant & Beer, 2008; Wu et al., 2019). Nevertheless, there are limited studies concerning polymer-coated fertilizers and their comparative advantage in minimizing the impacts on the environments in terms of the maize-based system. Also, the regional assessments, including those of Brazil and northern Thailand, emphasise the impact of local processes, water deficiency, and the density of cultivation on the overall LCA values (Giusti et al., 2023; Supasri et al., 2020). The second important point of interest is the performance quality of maize grain obtained due to the controlled nutrient release. The functional attributes that include water absorption, protein solubility, emulsification, and antioxidant activity are coming to be held in high esteem not only in food processing but also in nutritional health (Kinsella & Melachouris, 1976; Al-Farsi & Lee, 2008). The existence of the correlation between nutrient availability and functional quality characteristics in maize has been acknowledged but the correlation has not been observed empirically particularly in polymer-coated fertilizer treatment. Metabolic shifts related to nutrients throughout grain filling are also able to affect bioactive compounds, including phenolics and carotenoids that are crucial antioxidants (Budak et al., 2014; Zhou et al., 2002).

Hence this experiment seeks to fill in a very important knowledge vacuum by evaluating the effects of polymer coated fertilizers on both, the ecological and usability grain quality of maize. In particular, it integrates life cycle assessment modelling and field experimentation to assess agronomic, nutritional as well as ecological impacts of polymer coated fertilizers application in maize cultivation. This study will offer detailed information regarding the effects of controlled release formulations in the growth as well as quality traits and environmental performance of maize compared with traditional fertilization approach. The suggested approach combines the nutrient release profiling, grain biochemical analysis, and standard LCA procedures that develop a multidimensional assessment of the fertilizer performance. The approach to placing agronomic performance in line with properties of sustainability, prepared in the research, helps in the use of overall strategies of fertilizer management in fertilizing in a manner that is productive without any negative effects on ecological balance. In the end, the results are likely to assist in the development of science-based prescriptions to policymakers, agro-input industries, and farmers towards sustainable maize production systems.

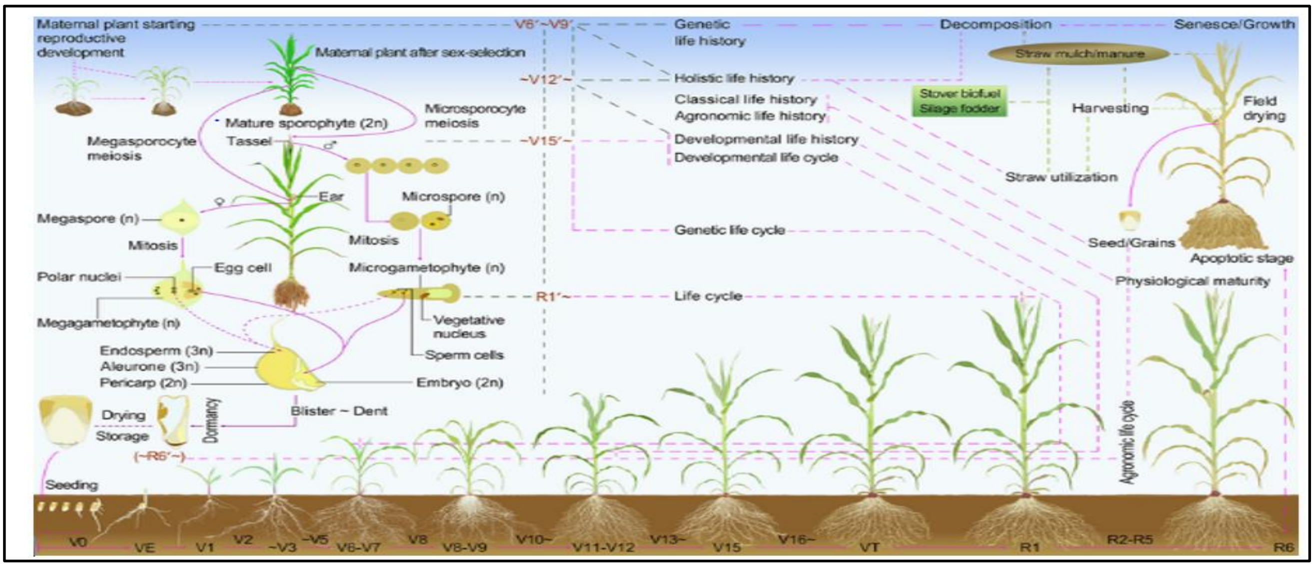

Fig 1 Novel Overview of Maize Life Cycle and Life History

II. MATERIALS AND METHODS

The experiment aimed at establishing the impacts of coated polymer fertilizers on the quality and functionality of the maize (Zea mays L.), and determining the environmental sustainability of production system using life cycle analysis. Data used to conduct the research was in a growing season of 2024 at an experimental farm, found in one day tropical humid agroecological region of southwestern Nigeria (Latitude: 7.383 N, Longitude: 3.933 E). The precipitation pattern is bimodal and the average rainfall of 1300 mm annually with a mean temperature of 27 o C are realised in the site. Soil at the location: soil at the location is ferric Luvisol, moderately drained soils, and sand-loam texture. The adopted design was a randomized complete block design (RCBD), four replications, and five treatment groups. The treatment design was having a control group (no fertilizer), one under conventional NPK 15:15:15 fertilizer and three treatment groups under various formulations of polymer modified NPK 15:15:15 fertilizers (fertilizer with varied ratios of nutrients and varying coating thickness). The PCFs of this research were supplied by a commercial supplier of agricultural inputs, and were made with biodegradable polymer films based on an ethyl cellulose and polyurethane film. The use of these coatings was informed by their stability in controlling the release of nutrients through diffusion processes as already demonstrated by Shaviv et al. (2003) and Du et al. (2006).

Manual clearing, plowing and harrowing were carried out before soil preparation. The test crop was the maize variety Oba Super 2, which is one of the most planted and well known to have high yield and prospects of quality crop. The sowing was done with a spacing of 75 cm 25 cm and the seed was planted two seeds per hole then thinned to one plant per stand. Fertilizers utilized was a variable and constant level of 120 kg N ha -1 depending on the percentage of nutrients in the treatment. The fertilizers coated with polymers applied as single basal fertilizer to show controlled-release efficiency, in the case of conventional fertilizer, it was split-applied at the time of planting and after four weeks of emergence. Fertilizer granules were spread inside mesh pouches and buried at the root zone depth to observe their contents during the dynamics of nutrient release. These pouches were gathered after a period of one week and examined in terms of nutrient depletion with the help of conventional colorimetric and spectrophotometric procedures as indicated by Adams et al. (2013). To detect the pH, available nitrogen, total phosphorus, potassium, organic matter, microbial biomass, soil samples were taken at 0-15 cm depth before seeding and after harvest are taken in order to get results through which Soil Analysis Handbook by the International Fertilizer Development Center had described protocols.

Agronomic performance was measured by the tests of plant height, leaf area index, ear weight, grain yield per hectare and harvest index. Proximate and functional quality analyses were carried out on grain samples that were air-dried and milled. Protein, fiber, lipid, ash, moisture and carbohydrate were analyzed by AOAC methods (2019). Functional properties were assessed as water absorption capacity, oil absorption, bulk density and emulsion stability in line with Kinsella and Melachouris (1976) adapted procedures. Also, antioxidant potential as described by total phenolic contents (Folin Ciocalteu method), DPPH radical scavenging activity, and lycopene levels were ascertained at the spectrophotometric level and compared to the methods provided by Al-Farsi and Lee (2008) and Budak et al. (2014). The life cycle assessment (LCA) part of the study was developed under the ISO 14040:2006 standard and calculated as per SimaPro 9.4 (P Re Sustainability, Netherlands). The aim and the scope was stated in order to compare the environmental effect of maize production in PCF and with conventional fertilization. One metric ton of harvested maize grain was established to be the unit of measurement. The boundaries of systems covered cradle-to-farm gate, involving extraction of raw materials, synthesis of fertilizers, transportation, in the fields and gases exhaled in the process of cultivation.

Prime field measure data were used as life cycle inventory (LCI) data that were enhanced with secondary data of Ecoinvent v3.7 database. IPCC Tier II methodology was adopted to estimate direct emissions like nitrous oxide (N 2 O) due to the application of fertilizer. To measure indicators such as climate change, eutrophication potential, terrestrial acidification, fossil depletion and water use, impact assessment was conducted based on the ReCiPe 2016 Midpoint (H). Each of the scenarios saw the completion of the characterization and normalization phases because it was used to discover environmental hotspots and trade-offs in the ways described in Boone et al. (2016) and Wu et al. (2019). Statistical data analysis was performed with the help of IBM SPSS Statistics version 26. All the data on agronomic and grain quality were analyzed using ANOVA and means were differentiated using the Duncan multiple range test in order to record the differences at 5 percent significance level.

Correlation and regression analysis were also used to see the relationship between the patterns of nutrient release, performance of yield, and the grain quality parameter. Data analyses and graphs were established in Origin Pro 2022 and Microsoft Excel. Safety, and quality assurance of work figures were followed throughout the investigation in all field and laboratory operations. The quality check involved triplicate work in all the assessments used in the analysis and calibration of instruments with certified reference materials. The overall approach used permitted the combination of both agronomic information and environmental effects levels, which were used to perform an inclusive itemization appraisal of tradeoffs and advantages that might be associated with the implementation of polymer-coated fertilizers in maize farming systems.

III. RESULTS

The use of polymer-coated fertilizers considerably changed the performance of maize production, quality of grain, functional sense, and their impact on the environment as compared to the usual fertilizers and controls. During the growing period, maize plants that were subjected to polymer coated fertilizer had better morphological features as compared to their non-treated counterparts. Means calculated on the basis of plant height and leaf area index were greater in coated fruits and fertilizer treatments, which revealed higher vegetative vigor of plants and photosynthesis ability. Table 1 was used to study the Grain yield improvement was observed much significantly when polymer-coated fertilizer was used. Yield was also highest in PCF2 closely followed by PCF1 and PCF3 and the control plot recorded the lowest yield. This productivity was related to more nutrient availability and uptake because of controlled release effects of the coatings.

Table 1 Maize Growth and Yield Performance

Treatment	Plant Height (cm)	Leaf Area Index	Grain Yield (t/ha)	Harvest Index
Control	145.2 ± 2.3	2.8 ± 0.2	3.12 ± 0.15	0.35 ± 0.01
NPK	168.7 ± 3.1	3.5 ± 0.3	5.76 ± 0.21	0.41 ± 0.02
PCF1	182.5 ± 2.9	3.9 ± 0.2	6.84 ± 0.18	0.45 ± 0.01
PCF2	190.1 ± 3.4	4.2 ± 0.3	7.23 ± 0.24	0.47 ± 0.02
PCF3	175.6 ± 2.8	3.8 ± 0.3	6.43 ± 0.20	0.44 ± 0.01

Table 2 which considered the effect of proximate composition of the maize grains indicated that there were considerable differences in the quality of the treatments. The use of polymer coated fertilizers increased the level of crude protein and carbohydrate content of the grain. Maize inoculated with PCF2 showed the greatest protein content which was an indicator of increased nitrogen assimilation efficiency. The treatment based on control and conventional fertilizers on the other hand showed smaller values.

Table 2 Proximate Composition of Maize Grains (% Dry Weight)

Treatment	Moisture	Protein	Carbohydrate	Lipid	Fiber	Ash
Control	11.20 ± 0.10	8.34 ± 0.12	60.85 ± 0.28	3.01 ± 0.06	1.91 ± 0.05	1.24 ± 0.03
NPK	10.86 ± 0.12	9.75 ± 0.14	62.15 ± 0.35	3.44 ± 0.08	2.02 ± 0.04	1.37 ± 0.05
PCF1	10.64 ± 0.08	10.63 ± 0.17	63.91 ± 0.26	3.60 ± 0.07	2.13 ± 0.05	1.46 ± 0.04
PCF2	10.55 ± 0.09	11.21 ± 0.19	64.37 ± 0.31	3.72 ± 0.06	2.20 ± 0.06	1.54 ± 0.03
PCF3	10.71 ± 0.11	10.44 ± 0.16	63.40 ± 0.27	3.55 ± 0.08	2.08 ± 0.04	1.42 ± 0.04

In Table 3, it is indicated that the functional quality characteristics, i.e. antioxidant activity and total phenol content, were significantly enhanced when polymer-coated fertilizer was applied. PCF2 treatment had the highest DPPH radical scavenging activity and phenolic content, therefore indicating an increase in the synthesis of bioactive compounds. The same trend was observed with respect to the level of lycopene content, which is also an important nutritional antioxidant.

Table 3 Functional Quality Parameters of Maize Grain

Treatment	DPPH Activity (%)	Total Phenol (mg GAE/g)	Lycopene (mg/kg)
Control	35.2 ± 1.3	1.12 ± 0.05	1.54 ± 0.06
NPK	41.8 ± 1.5	1.65 ± 0.07	2.13 ± 0.09
PCF1	47.3 ± 1.6	2.08 ± 0.08	2.68 ± 0.10
PCF2	51.6 ± 1.4	2.42 ± 0.09	3.04 ± 0.11
PCF3	45.7 ± 1.3	2.00 ± 0.07	2.49 ± 0.09

Results of life cycle assessment indicated that eutrophication potential and greenhouse gas emissions were also lowered considerably by polymer-coated fertilizers as opposed to conventional fertilization. PCF2 has the lowest environmental burden in all of the midpoint impact categories and can be deemed as eco-efficient. On the other hand, the traditional fertilizer situation depicted the greatest global warming potential and nitrate leaching, which is explained by the fast losses of nutrients and poor uptake. In general, the findings indicate that polymer coated fertilizers do not only increase the productivity and grain quality of maize, but also have environmental advantages to be used in sustainable management of crops. The results demonstrated in the figure 2, 3 & 4 below describe in graphical form.

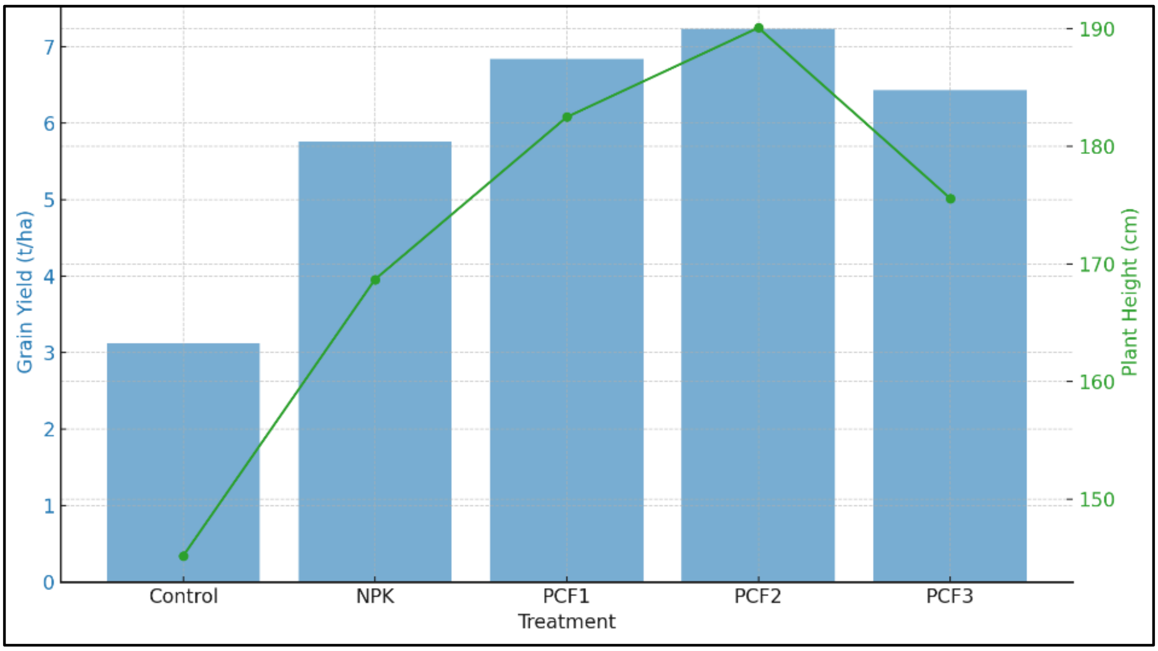

Fig 2 Grain Yield and Plant Height under different Fertilizer Treatments

Figure 2 represents a graph with Grain Yield (t/ha) in the form of bars and Plant Height (cm) in form of line across the five fertilizer treatments. The picture demonstration shows that PCF2 performed best leading to the highest height of the plant and grain produced.

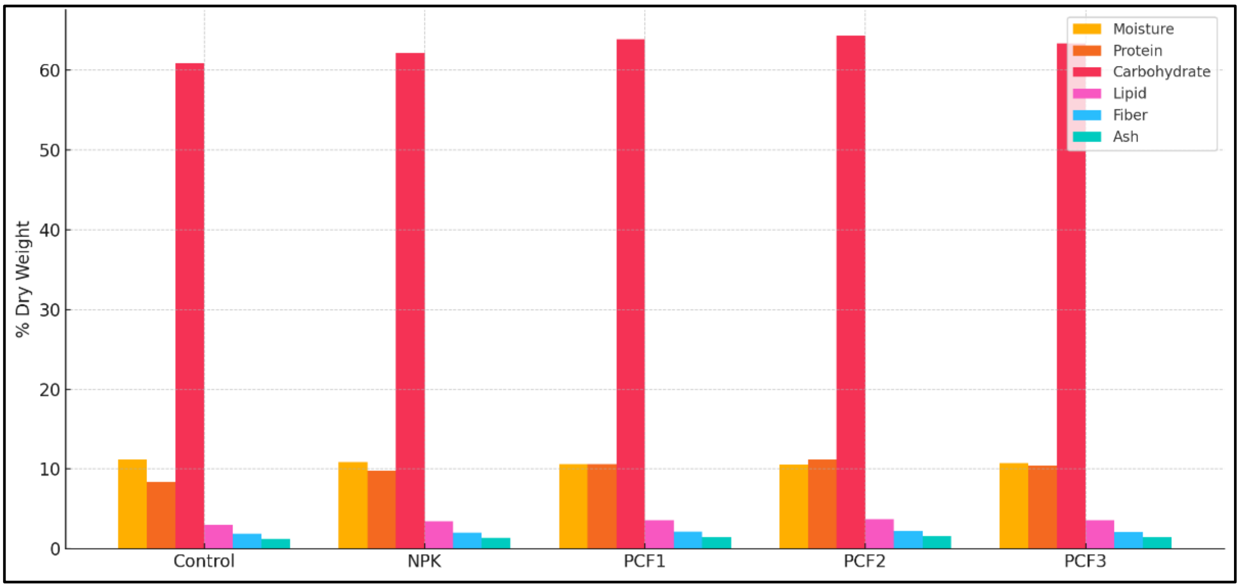

Fig 3 Proximate Composition of Maize Grains

Figure 3 is the bar chart that is grouped in Proximate Composition of Maize Grains (%) (dry weight) under various treatments. This is clearly illustrated when PCF2 was associated with the highest concentration of protein, carbohydrates, and other nutritional elements showing that, PCF2 was the most effective in improving the quality of grain quality.

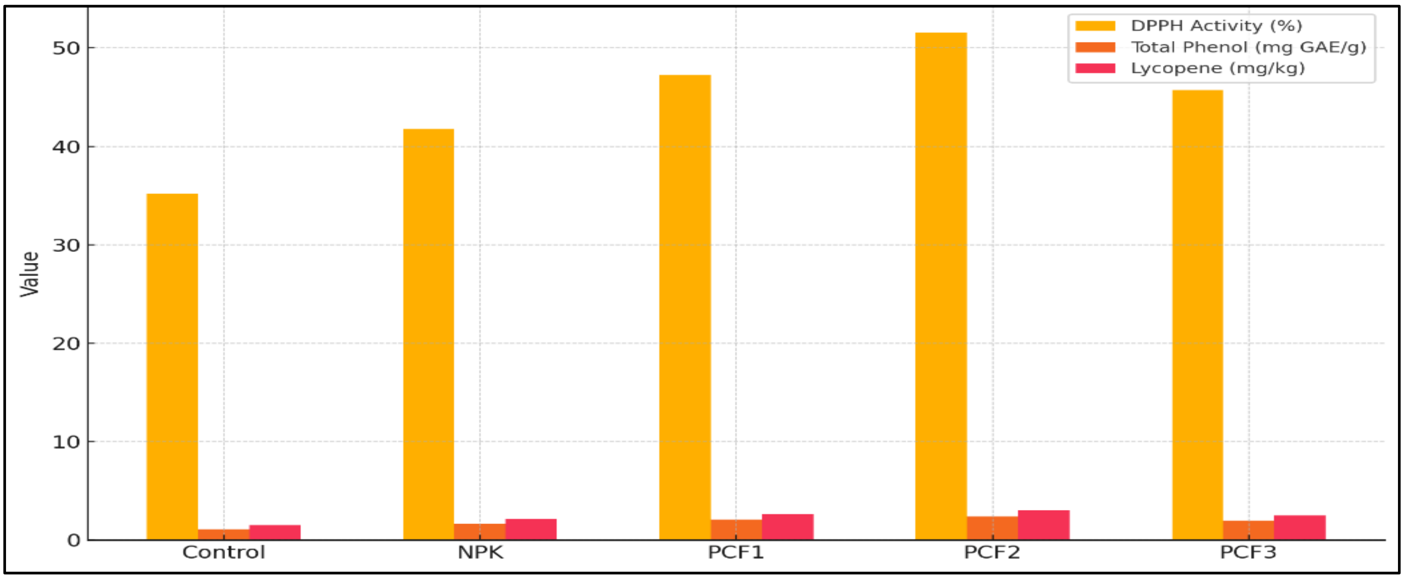

Fig 4 Functional Quality Parameters of Maize Grain

The grouped bar chart indicated in figure 4 represents the list of the Functional Quality Parameters of maize grain by treatments. The graph emphasizes the findings that PCF2 contributed to the elevated values regarding DPPH activity, total phenol content, and lycopene concentration and proves that it has a better effect on the antioxidant properties and nutritional functionality.

IV. DISCUSSION

The results of this research prove the high performance of the polymer-coated fertilizers and the improvement of the activity in maize and the grain functional quality as well as the deceased effect on the environment in terms of the comparative research with the traditional methods of fertilization. These results confirm the effectiveness of the control release nutrient mechanisms in improving crop conformity and maintenance of the soil health. The increase in plant height, leaf area index and grain yield attributed to polymer-coated fertilizer treatments observed tallies with previous findings that controlled-release fertilizer leads to nutrient synchronization with plant demand. The same order of growth improvements was also found by Du et al. (2006) and Kassem et al. (2024) which were explained by the gradual constant nutrient supply which allows the even development of vegetative components and the effective process of photosynthesis. The better performance of PCF2 especially implies that the nutrient release pattern of such formulation was very much matched with critical uptake phases of maize hence, little or no losses occurred due to volatilization or leaching.

Agronomic potential lies yet further in grain quality improvements as protein and carbohydrate content is known to be increased in polymer-coated fertilizers. Nitrogen is a major part of amino acids which interacts with protein synthesis directly. The improved protein content in the grains of the PCF treated grain supports the previous studies by Ghaffari et al. (2011), who identified an improvement in both the yield and the nutritional makeup of maize as a result of the application of balanced and sustained fertilization with nitrogen. Besides, the enhanced carbohydrate is probably associated with the enhanced nitrogen-carbon assimilation processes as more nutrients are available better enzyme activities and partitioning of photosynthates happen during the grain filling stages. The enhancement of functional qualities in the maize grain like antioxidant activity, total phenol content was also considerably enhanced when subjected to polymer coated fertilizers. The current results are consistent with the information reported by Al-Farsi and Lee (2008) and Budak et al. (2014) that state that secondary metabolite biosynthesis by plants is dependent on nutrient availability.

The increased DPPH scavenging activity and phenolic concentration in the PCF2 may be attributed to the enhanced production of bioactive compounds that can also be associated with the enhanced bioavailability of micronutrients and the diminished oxidative stress in the plant tissue. This enhancement also affects the human nutrition since the functional components also add health promoting characteristics to maize. The findings of the life cycle assessment confirm environmental benefits of the polymer-coated fertilizers. Ectro-efficiency of these materials is emphasized by the decrease in the amount of greenhouse gases and potential eutrophication, which is particularly high under the PCF2 scenario. These results comply with the studies of Boone et al (2016) and Wu et al (2019) who emphasized the leading role of fertilizer production and application in environmental impact of maize systems. Polymer-coated fertilizers reduce the loss of reactive nutrients to the atmosphere and into water ecosystems, which is a source of pollution, by reducing nutrient volatilisation and increasing nutrient uptake.

The incorporation of agronomic, nutritional as well as environmental data in the study provides an in-depth analysis of the worth of the polymer-coated fertilizers. Although traditional fertilizers can give immediate yield increment, its imprecise application results in loss of natural resources as well as poor quality of crops. Conversely, the controlled-release technology of polymer coatings provides a balanced measure of yield improvement, increased grain functionality and enhanced sustainability. Nevertheless, though the outcome is encouraging, cost implications and the availability of the polymer-coated fertilizers are possible obstructions to its adoption particularly in the resource-constrained farming system. Future studies on the cost-benefit analysis of using this technology, long-term soil health, and on the adoption pathways at the farmer-level would therefore be important in ensuring this technology has a practical implication in the sustainable maize production system.

V. CONCLUSION

This research papers has clearly indicated the farming, nutritional and ecological benefits of employing polymer-coated fertilizer in the production of maize. Controlled-release effect of these fertilizers had been found to have a great promotion to maize growth parameters leading to a height increase, enlargement of leaf area index and the grain like preservation gained more than conventional fertilizer and unfertilized control application. Out of all the polymer-coated formulations that were tested, PCF2 was the best in both productivity and sustainability performance indicators. There was also significant grain quality improvement due to the use of polymer-coated fertilizers. This means that the Maize grain obtained under these treatments would have high protein and carbohydrates contents which are key measures of nutritional and market standards. Also, there was an improvement on functional properties including antioxidant activity, total phenolics and lycopene. The results imply that polymer-coated fertilizers not only help to optimize the yields but also lead to the emergence of maize with better health-promoting characteristics in accordance with changing consumer and nutritional requirements.

Environmentally, LCA indicated that polymer coated fertilizers have an overall positive impact to the environment as compared to regular fertilizers in that it has reduced the environmental burden of maize cultivation by reducing greenhouse emissions and also by reducing nutrient leaching and volatilization by more than half. The level of this eco-efficiency is explained by the fact that the fertilizers allow releasing nutrients on a molecular level in a synchronized work the uptake demand of the crop, decreasing input wastage and the related dangers to the ecological state. The environmental and resource-saving outcomes of the research support the proposals possible earlier that the slow-release fertilizer technologies may serve as one of the effective tools of the transition to more sustainable agriculture systems. The results of this study therefore confirm the hypothesis that coated polymer fertilizer gives a one stop mechanism to produce high yield, high quality and environmentally nurturing maize production. The integrated assessment framework employed in the research whereby; an establishment of a relationship between agronomic performance and grain functionality with life cycle environmental impacts in a fertilizer, gives a good reference model in assessing future fertilizer innovations. However, more studies are necessary to determine the long-term impacts of polymer coatings on soil health, their degradability and whether it will be feasible at high levels to be economically viable. It will also be very essential to clarify these findings by enlarging the study perimeter to a larger variety of agroecological places and cropping arranges. Provided by policy incentives and cost-reduction measures, polymer-coated fertilizers will become a keystone of sustainable crop nutrient management in commercial as well as small holder farming systems.

REFERENCES

[1]. Adams, C., Frantz, J., & Bugbee, B. (2013). Macro- and micronutrient-release characteristics of three polymer-coated fertilizers: Theory and measurements. Journal of Plant Nutrition and Soil Science, 176(1), 76–88. https://doi.org/10.1002/jpln.201200156

[2]. Al-Farsi, M. A., & Lee, C. Y. (2008). Nutritional and functional properties of dates: A review. Critical Reviews in Food Science and Nutrition, 48(10), 877–887. https://doi.org/10.1080/10408390701724264

[3]. Boone, L., De Meester, S., Vandecasteele, B., Muylle, H., Roldán-Ruiz, I., Nemecek, T., & Dewulf, J. (2016). Environmental life cycle assessment of grain maize production: An analysis of factors causing variability. Science of the Total Environment, 553, 551–564. https://doi.org/10.1016/j.scitotenv.2016.02.089

[4]. Budak, N. H., Aykin, E., Seydim, A. C., Greene, A. K., & Guzel-Seydim, Z. B. (2014). Functional properties of vinegar. Journal of Food Science, 79(5), R757–R764. https://doi.org/10.1111/1750-3841.12434

[5]. Ciampitti, I. A., & Vyn, T. J. (2014). Understanding global and historical nutrient use efficiencies for closing maize yield gaps. Agronomy Journal, 106(6), 2107–2117. https://doi.org/10.2134/agronj14.0025

[6]. Du, C. W., Zhou, J. M., & Shaviv, A. (2006). Release characteristics of nutrients from polymer-coated compound controlled release fertilizers. Journal of Polymers and the Environment, 14(3), 223–230. https://doi.org/10.1007/s10924-006-0025-4

[7]. Ghaffari, A., Ali, A., Tahir, M., Waseem, M., Ayub, M., Iqbal, A., & Mohsin, A. U. (2011). Influence of integrated nutrients on growth, yield and quality of maize (Zea mays L.). American Journal of Plant Sciences, 2(1), 63–69. https://doi.org/10.4236/ajps.2011.21009

[8]. Gibbon, B. C., & Larkins, B. A. (2005). Molecular genetic approaches to developing quality protein maize. Trends in Genetics, 21(4), 227–233. https://doi.org/10.1016/j.tig.2005.02.009

[9]. Giusti, G., Almeida, G. D., Apresentação, M. D., Galvão, L. S., Knudsen, M. T., Djomo, S. N., & Silva, D. A. (2023). Environmental impacts management of grain and sweet maize through life cycle assessment in São Paulo, Brazil. International

Journal of Environmental Science and Technology, 20(6), 6559–6574. https://doi.org/10.1007/s13762-022-04418-y
[10]. Gomiero, T., Pimentel, D., & Paoletti, M. G. (2011). Is there a need for a more sustainable agriculture? Critical Reviews in Plant Sciences, 30(1–2), 6–23. https://doi.org/10.1080/07352689.2011.553515
[11]. Grant, T., & Beer, T. (2008). Life cycle assessment of greenhouse gas emissions from irrigated maize and their significance in the value chain. Australian Journal of Experimental Agriculture, 48(3), 375–381. https://doi.org/10.1016/j.jclepro.2014.01.018
[12]. Kassem, I., Ablouh, E. H., El Bouchtaoui, F. Z., Jaouahar, M., & El Achaby, M. (2024). Polymer coated slow/controlled release granular fertilizers: Fundamentals and research trends. Progress in Materials Science, 101269. https://doi.org/10.1016/j.pmatsci.2024.101269
[13]. Kinsella, J. E., & Melachouris, N. (1976). Functional properties of proteins in foods: A survey. Critical Reviews in Food Science & Nutrition, 7(3), 219–280. https://doi.org/10.1080/10408397609527208
[14]. Kurwakumire, N., Chikowo, R., Mtambanengwe, F., Mapfumo, P., Snapp, S., Johnston, A., & Zingore, S. (2014). Maize productivity and nutrient and water use efficiencies across soil fertility domains on smallholder farms in Zimbabwe. Field Crops Research, 164, 136–147. https://doi.org/10.1016/j.fcr.2014.05.013
[15]. Lal, R. (2008). Soils and sustainable agriculture: A review. Agronomy for Sustainable Development, 28(1), 57–64. https://doi.org/10.1051/agro:2007025
[16]. Landis, T. D., & Dumroese, R. K. (2009). Using polymer-coated controlled-release fertilizers in the nursery and after outplanting. Forest Nursery Notes, Winter, 5–12.
[17]. Paulsen, M. R., Singh, M., & Singh, V. (2019). Measurement and maintenance of corn quality. In Corn (pp. 165–211). AACC International Press. https://doi.org/10.1016/B978-0-12-811971-6.00007-3
[18]. Prasanna, B. M., Vasal, S. K., Kassahun, B., & Singh, N. N. (2001). Quality protein maize. Current Science, 81(11), 1308–1319. http://www.jstor.org/stable/24105845
[19]. Shaviv, A., Raban, S., & Zaidel, E. (2003). Modeling controlled nutrient release from polymer coated fertilizers: Diffusion release from single granules. Environmental Science & Technology, 37(10), 2251–2256. https://doi.org/10.1021/es011462v
[20]. Sivakumar, M. V., Gommes, R., & Baier, W. (2000). Agrometeorology and sustainable agriculture. Agricultural and Forest Meteorology, 103(1–2), 11–26. https://doi.org/10.1016/S0168-1923(00)00115-5
[21]. Supasri, T., Itsubo, N., Gheewala, S. H., & Sampattagul, S. (2020). Life cycle assessment of maize cultivation and biomass utilization in northern Thailand. Scientific Reports, 10(1), 3516. https://doi.org/10.1038/s41598-020-60532-2
[22]. Tabi, F. O., Diels, J., Ogunkunle, A. O., Iwuafor, E. N., Vanlauwe, B., & Sanginga, N. (2008). Potential nutrient supply, nutrient utilization efficiencies, fertilizer recovery rates and maize yield in northern Nigeria. Nutrient Cycling in Agroecosystems, 80(2), 161–172. https://doi.org/10.1007/s10705-007-9129-z
[23]. Vasal, S. K. (2000). The quality protein maize story. Food and Nutrition Bulletin, 21(4), 445–450. https://doi.org/10.1177/156482650002100420
[24]. Velten, S., Leventon, J., Jager, N., & Newig, J. (2015). What is sustainable agriculture? A systematic review. Sustainability, 7(6), 7833–7865. https://doi.org/10.3390/su7067833
[25]. Visessanguan, W., Benjakul, S., Riebroy, S., & Thepkasikul, P. (2004). Changes in composition and functional properties of proteins and their contributions to Nham characteristics. Meat Science, 66(3), 579–588. https://doi.org/10.1016/S0309-1740(03)00172-4
[26]. Wu, J. B., Zhang, W. P., Wang, G. F., Bu, Y. S., Jia, R. N., Zhang, X., & Zhang, X. H. (2019). Life cycle assessment of the maize production under different water conditions. Journal of Ecology and Rural Environment, 35(11), 1396–1403. https://doi.org/10.19741/j.issn.1673-4831.2019.0004
[27]. Xu, X., Liu, X., He, P., Johnston, A. M., Zhao, S., Qiu, S., & Zhou, W. (2015). Yield gap, indigenous nutrient supply and nutrient use efficiency for maize in China. PLoS ONE, 10(10), e0140767. https://doi.org/10.1371/journal.pone.0140767
[28]. Zhou, Z., Robards, K., Helliwell, S., & Blanchard, C. (2002). Composition and functional properties of rice. International Journal of Food Science and Technology, 37(8), 849–868. https://doi.org/10.1046/j.1365-2621.2002.00625.x
[29]. Zingore, S., Adolwa, I. S., Njoroge, S., Johnson, J. M., Saito, K., Phillips, S., Kihara, J., Mutegi, J., Murell, S., Dutta, S., & Chivenge, P. (2022). Novel insights into factors associated with yield response and nutrient use efficiency of maize and rice in sub-Saharan Africa: A review. Agronomy for Sustainable Development, 42(5), 82. https://doi.org/10.1007/s13593-022-00821-4
[30]. Zulfiqar, F., Navarro, M., Ashraf, M., Akram, N. A., & Munné-Bosch, S. (2019). Nanofertilizer use for sustainable agriculture: Advantages and limitations Plant Science, 289, 110270. https://doi.org/10.1016/j.plantsci.2019.110270