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Preserving soil properties and enhancing cauliflower yield with black plastic mulch in Bangladesh

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ABSTRACT

Poor soil health and inefficient farming practices significantly challenge sustainable agriculture and crop productivity in Bangladesh. This study evaluated the impact of various mulching techniques on soil properties, cauliflower yield, and carbon sequestration in Bangladesh to identify the optimal mulching strategy for sustainable cauliflower production and carbon sequestration. A field experiment in the Bogura district evaluated the effects of various mulching materials—newspaper, rice husk, rice straw, black plastic, craft paper, and no mulch—on soil physicochemical properties and cauliflower production. Data measurement and monitoring assessed soil properties, mulch degradation rates, and cauliflower quality, with organic carbon determined using Walkley and Black's method. Results showed significant impacts of mulching on soil parameters and cauliflower yield. Black plastic mulch increased soil temperature by approximately 6°C and conserved soil moisture by 13.2% compared to the no-mulch (control). Organic mulches, especially rice husk, were superior in conserving soil carbon (21.3 g Kg^{-1}) and increasing available nitrogen (22.4 mg Kg^{-1}), phosphorus (36.5 mg Kg^{-1}), and soil pH (7.4). Although all treatments increased electrical conductivity (EC), the control showed the highest EC value (405.5 µS cm^{-1}). Among organic mulches, craft paper had the highest degradation rate followed by newspaper and rice straw mulches. Cauliflower yield varied with mulch type, with black plastic producing the highest yield (1162.0 g), followed by rice straw (1050.0 g), rice husk (983.0 g), craft paper (821.0 g), and newspaper (752.0 g). These findings suggested black plastic mulch for maximizing cauliflower production in Bangladesh and similar conditions.

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1. INTRODUCTION

The scarcity of natural resources, particularly land, water, and energy, poses significant challenges in many regions worldwide (Wang & Azam, 2024). Agriculture sector consumes around 70% of the global water supply, which is mostly affected by this scarcity (El-Beltagi et al., 2022). Thus, efficient management of water resources is essential for sustainable agriculture growth and human well-being (Deka et al., 2022). In Bangladesh, irrigation water use is less efficient than other agricultural inputs like land, labor, fertilizer, and tillage operations (Chowdhury, 2009) which exacerbated water scarcity in the southwest and northwest regions during the dry season. Addressing these challenges is crucial for improving agricultural sustainability. Water conservation practices like mulching can enhance crop yield and alleviate water constraints.

Mulching is the practice of applying materials to the soil surface, which conserves soil water by reducing evaporation and altering soil temperature (Kader et al., 2017). It became very popular in commercial vegetable cultivation for improving water use efficiency, crop yield as well as quality (Islam et al., 2021). Traditional organic mulches add nutrients to the soil as they degrade, improving soil tilth and moisture retention (Lamont, 2005). Recently, straw and plastic film

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have become the most commonly used and popular mulching materials (Kader, 2020; Zheng et al., 2021). Organic substances, for example, wood manufacturing waste (sawdust), agricultural waste (stalks & straw), processing residues (rice husks), animal wastes/litters (manure), etc. derive organic mulching materials which are less expensive as well as environment-friendly (Kader et al., 2017; Kumar & Usadadiya, 2023). However, the effectiveness of different mulch materials on soil health and crop profitability varies depending on multiple factors such as type of film, color, emissivity, thickness, and costs.

Despite the benefits, mulching can also influence greenhouse gas emissions by affecting soil respiration and CO_2 levels through changes in soil temperature, moisture, porosity, and aeration (Guo & Liu, 2022). With rising global temperatures and significant anthropogenic CO_2 emissions, effective agricultural practices are needed to sequester carbon and mitigate climate change (Panchal et al., 2022). Agriculture plays a crucial role in the carbon cycle, with the potential to increase carbon storage through photosynthesis, land use changes, and adjustments to the water cycle (Rodrigues et al., 2023). Thus, specific agricultural practices including mulching, can help limit global warming by acting as both sources and sinks of greenhouse gases from the soil.

Cauliflower (*Brassica Oleracea* L.) is a winter vegetable crop cultivated in Bangladesh due to its high economic return, agro-climatic adaptability, and nutritional benefits (Hossain et al., 2019). However, challenges such as pest management, water scarcity, and post-harvest losses necessitate integrated pest management, modern agricultural techniques like mulching and drip irrigation, and improved storage facilities (Hossain et al., 2019). Additionally, there is a lack of understanding and utilization of effective mulching techniques among farmers, which poses a challenge (Salem et al., 2021). Mulching can address water conservation and soil health management issues which increase agricultural efficiency and output, particularly in rural areas. While mulching enhances soil organic carbon (SOC) and soil nitrogen (N), leading to improved plant growth in later stages, it can inhibit early season growth and potentially reduce yield (Liu et al., 2021). Increasing SOC through carbon sequestration is crucial for mitigating atmospheric CO_2 and promoting soil health (Lal et al., 2015).

This research aims to identify the best mulching practices for maintaining high-quality cauliflower production while achieving a high rate of carbon sequestration. Unlike previous studies, this research provides a comprehensive evaluation of various cost-effective and locally available mulching materials, including newspaper, rice husk, rice straw, black plastic, and craft paper in the specific agro-climatic context of Bangladesh. The novelty lies in the detailed comparison of these mulches, focusing on their impact on soil physio-chemical properties, cauliflower yield, and carbon sequestration. This study uniquely highlights the superior performance of various organic and plastic mulches in enhancing soil temperature, soil moisture conservation, and cauliflower yield. Findings from this study could be used to recommend the optimal mulch materials to improve higher production and soil health management for the cauliflower farmers in the Northern Bogura district of Bangladesh.

2. MATERIALS AND METHODS

2.1. Experimental approach and designs

The field experiment was carried out at the Rural Development Academy (RDA) experimental farm which is in the Sherpur Upazila of Bogura District, Bangladesh. It is situated between 24°32' and 25°07' N and 88°58' and 89°45' E. Bogura district is 2898.25 km^2 in size, with an average yearly temperature of 34.6°C and a low of 11.9°C, with an annual rainfall of 1610 mm. The pH value of the soil of Bogura ranges from 4.50 to 5.58, Electrical conductivity (EC) lies between 52 to 625 S at 0-30 cm soil depths. The organic carbon content of the site varies between 0.17 and 2.1% (Begum et al., 2014). Most of the land in Bogura is alluvial, which is fertile and suitable for farming. Lateritic and sandy soils are also present in the area.

2.2. Crop Selection and Variety

In this experiment, F1 Hybrid Cauliflower *(Brassica oleracea* L.*)* was grown in the experimental field. F1 Hybrid Cauliflower, the germination rate is set at 80%. The study established a minimum physical and genetic purity criterion of 98% for the cauliflower seeds in addition to the minimum germination percentage. In October, seedlings of 15-day-old F1 Hybrid Cauliflower were sown in the field at a 45 cm × 45 cm spacing at a depth of 3-5 cm. The maturity age for this variety is 55-60 days. Three types of seedlings were transplanted –seedling 1 (plant height- 10 cm, root depth- 8 cm), seedling 2 (plant height- 9 cm, root depth- 9 cm) and, seedling 3 (plant height- 11 cm, root depth- 7 cm).

2.3. Treatments

About six treatments have been considered and followed a completely randomized design (CRD) with three replications presented in Table 1. Of the six treatments, four are organic mulch, and one is inorganic mulch, including a control group (Table 1). The control plot was left no-mulched (bare soil). Total number of plants in each treatment was 12.

2.4. Fertilizer Application

Throughout the entire duration of the experiment, a total of seven distinct fertilizers were meticulously applied in definite quantity presented in Table 2.

2.5. Experimental Plot Design

The experiment was conducted on a 380 × 560 cm plot, divided into six portions of 100 × 225 cm each, with a 10 cm distance between each portion. Three replications were used for robust data analysis (Fig. 1).

Table 1. Different treatments with mulch application rates following in the experiment

Treatments	Amount (g m^{-2})
Newspaper	196.1
Rice husk	980.4
Rice straw	784.3
Plastic (black color with 2 µm thickness)	198.8
Craft paper (brown)	235.3
Control (no-mulch)	-

Table 2. Different fertilizers following in the experiment

Fertilizer	Quantity (Kg treatment^{-1})
Organic fertilizer	8
Urea	1
TSP	1
MOP	1
Zinc	0.1
Boron	0.1
Gypsum	0.25

2.6. Data Collection

To assess the effects of six treatments on the physio-chemical properties of soil, the degradation rate of mulch and the quality of cauliflower were keenly observed and recorded every day on above mentioned parameters. The degradation rate for each type of organic mulch component was estimated by observing the initial thickness of the mulch and its degradation over different days in relation to irrigation and rainfall events. The organic carbon was determined using Walkley and Black's method following (Walkley & Black, 1934). The process relies on oxidizing organic carbon with a dichromate-sulfuric acid solution, followed by titration to measure the amount of unreacted dichromate. A portable soil meter (SEM2260, Sichuan, China) is used to measure different soil parameters like soil moisture, temperature, pH level, and nutrient content of N, P, and K. The data were collected from each treatment on a periodic basis throughout the season at 5 cm depth. A brief description of considerable parameters was studied and displayed in Table 3. Utilizing the right conversion ratios and the amount of FAS solution used during the titration, the organic carbon content was determined. The relationship between the conversion factor and the molecular weight of carbon relies on the concentration of the potassium dichromate solution.

2.7. Statistical Analysis

We employed SPSS 23.0 (SPSS Inc., Chicago, IL, USA) software to perform a statistical analysis of the data collected for various parameters. Descriptive statistics and homogeneity tests were conducted in SPSS. One-way analysis of variance (ANOVA) was performed to assess significant differences ($p < 0.05$) between treatment means. Post-hoc analysis using Duncan's test identified significant differences between specific treatments.

3. RESULTS

3.1. Soil pH

The pH levels of the soil exhibited variations following the application of different treatments. Initially, after the treatments were applied, newspaper (7.3) and craft paper (7.1) resulted in the highest soil pH. Over a period of three months, the soil pH for rice husk and rice straw showed a notable increase. The pH for rice husk rose by 17.5%, going from 6.3 to 7.4, while the pH for rice straw increased by 13.8%, changing from 6.5 to 7.3. In contrast, over the same three-month period, the pH levels for newspaper, black plastic, and craft paper decreased. The pH for newspaper dropped from 7.3 to 7.1, for black plastic from 6.8 to 6.5, and for craft paper from 7.1 to 7.0. Sequence of pH ranked: Rice Husk> Rice straw> Newspaper > Craft paper> Control> Black Plastic.

3.2. Soil Temperature

Distinct alterations in soil temperature were observed following the application of six different types of mulch. Notably, only newspapers exhibited a negative change, indicating a decrease in soil temperature. In contrast, the remaining five treatments—rice husk, rice straw, black plastic, craft paper, and control soil—demonstrated an increase in soil temperature after application (Table 5). Sequence: Black Plastic >Rice Husk> Rice straw> Craft paper> Newspaper > Control.

3.3. Soil Moisture

At the outset, the soil moisture levels were most pronounced beneath craft paper and in the no-mulched condition. Corresponding to the temperature trends, there was an elevation in soil moisture under plastic mulch following treatment. Notably, both rice husk and rice straw exhibited substantial positive changes in soil moisture over the three months post-application (Fig. 2). Sequence: Black Plastic >Rice Husk> Craft paper >Rice straw > Newspaper > Control.

3.4. Electrical Conductivity

Before treatment application, rice husk, and plastic exhibited the highest levels of electrical conductivity, while the remaining four treatments displayed comparable conductivity. Post-mulch application, a significant increase in electrical conductivity was observed for the rice husk and the control media, whereas the other four treatments demonstrated no significant changes, maintaining relatively similar conductivity levels (Table 5). Sequence: Control>Rice Husk> Rice straw >Craft paper > Newspaper > Black Plastic.

Table 3. Different data measurements and their descriptions

Data	Description
Physio-chemical properties	pH, temperature, moisture, available nutrients (N, P, K), electrical conductivity, and carbon sequestration.
Degradation rate	Degradation rates of the mulch components, including newspaper, rice husk, rice straw, craft paper, and black plastic were calculated by observing the initial & final thickness
Yield	The weight of the cauliflower was calculated by using a digital balance machine.

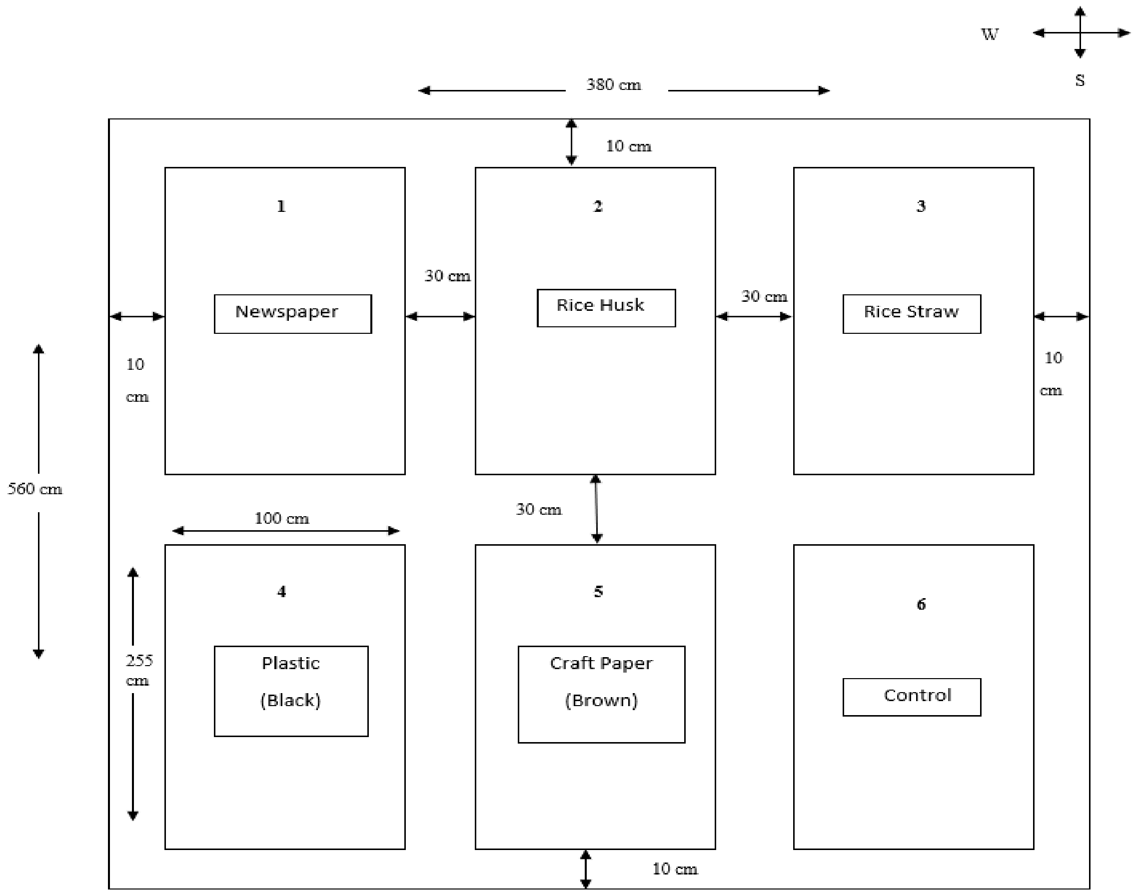

Figure 1. Field experimental layout of the plot and different treatments

3.5. Available N, P and K

Pre-mulching, the nitrogen (N) and phosphorus (P) levels in the soil were relatively consistent, with black plastic and craft paper exhibiting the highest levels of N and P, respectively (Table 5). Following mulch application, there was an augmentation in the availability of nutrients for both nitrogen and phosphorus in the cases of newspaper, rice husk, rice straw, and black plastic. Notably, a minor divergence was observed in the control media, where the nitrogen levels decreased, but phosphorus levels saw an increase. Sequence: Rice Husk > Rice straw > Newspaper> Craft paper > Black Plastic > Control. Prior to mulching, the soil's potassium levels were notably low, with newspaper and craft paper displaying the highest concentrations. After mulch application, there was a substantial increase in the availability of potassium across the treatments. Particularly noteworthy was the elevated increase in potassium levels observed in the conditions where rice husk, rice straw, and plastic mulch were applied (Table 5). Sequence: Black Plastic > Rice straw >Rice Husk > Newspaper > Craft paper > Control.

3.6. Carbon sequestration

Among the organic mulches, Rice husk exhibited the highest soil carbon concentration, with an average of (21.3 g kg^{-1}, followed closely by rice straw at (19.4 g kg^{-1}), newspaper, plastic, and craft paper, recording (18.6 g kg^{-1}), (18.0 g kg^{-1}), and (15.6 g kg^{-1}) respectively. In contrast, the control medium showed the lowest soil carbon content at (12.5 g kg^{-1}) (Fig. 3). The quantity of rice husked significantly increased by 90.6% after the treatment. Sequence: Rice Husk> Rice straw > Newspaper> Black Plastic> Craft Paper> Control.

Table 5. Effects of different mulching materials on Nitrogen, Phosphorus, Potassium, Temperature, Electrical Conductivity, and pH of cauliflower.

Treatments	Nitrogen (mg kg^{-1})		Phosphorus (mg kg^{-1})		Potassium (mg kg^{-1})		Temperature (°C)		Electrical Conductivity (μs cm^{-1})		pH	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
Newspaper	12.7c	18.4c	27.4d	34.7c	28.5a	31.7c	35.5a	33.3c	265.9b	313.2c	7.3a	7.1ab
Rice Husk	12.1d	22.4 a	26.8e	36.5a	26.9bc	33.5b	29.6e	37.5a	298.0a	385.6b	6.3c	7.4a
Rice straw	13.3b	20.2 b	29.6b	35.1 b	26.7c	34.9a	33.3b	35.6b	252.0b	324.9cd	6.5bc	7.4a
Black Plastic	14.7a	15.3e	28.6 c	32.2e	25.3d	35.2a	30.6d	37.6a	308.0a	304.2 d	6.8ab	6.5c
Craft Paper	11.2e	17.6d	30.3a	34.4d	27.3b	32.1c	32.1c	32.3d	248.8b	327.7c	7.1b	7.0ab
Control	13.3b	12.1f	29.5b	31.5f	24.8d	30.6d	30.8d	31.3e	260.5b	405.5a	6.4bc	6.9bc

Remarks: Difference small letters indicate significant differences at P < 0.05 by Duncan's post hoc test

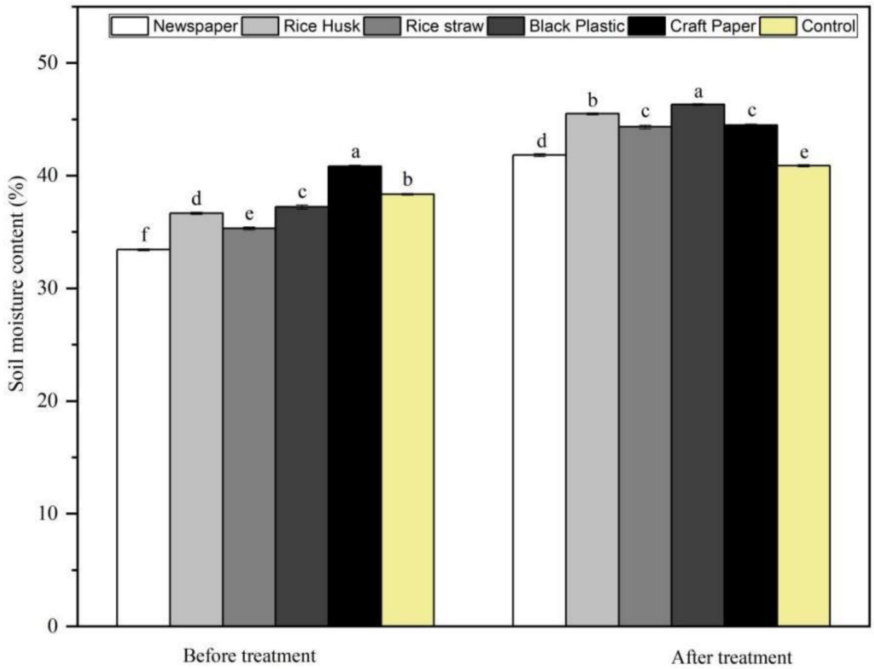

Figure 2. Impact of various mulching on the soil moisture content in cauliflower crops

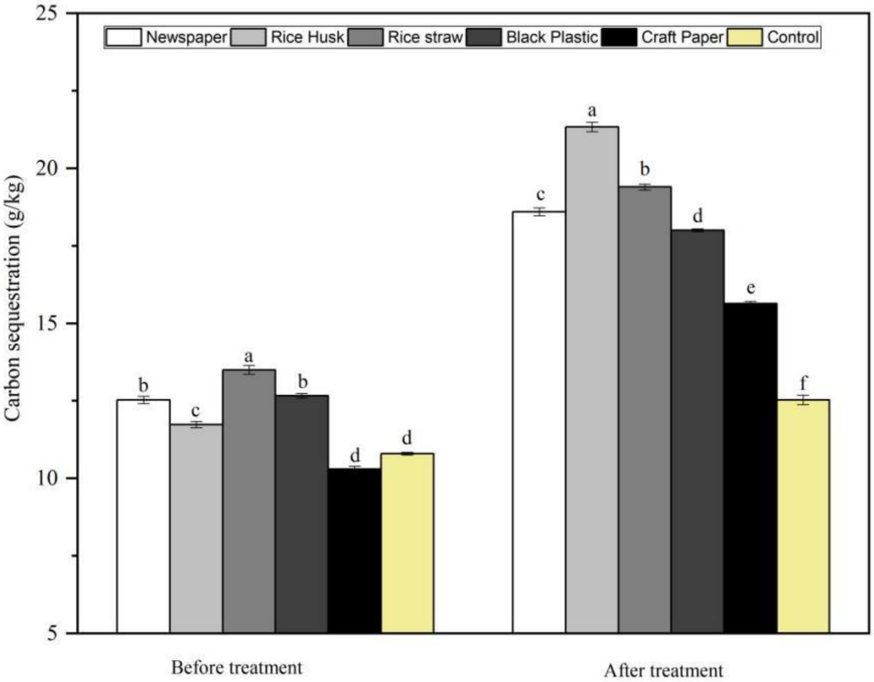

Figure 3. Impact of various mulching on soil carbon sequestration in cauliflower crops

3.7. Effect of Mulching on cauliflower yield

Significant variations in cauliflower yield were observed across diverse mulch types. The highest yield was achieved with black plastic (1162 g), followed by rice straw, rice husk, craft paper, and newspaper mulch. The control condition produced the lowest yield (629.9 g kg^{-1}), which was statistically comparable to the yields of newspapers (674.7 g) (Fig. 4). Sequence: Black Plastic > Rice Straw> Rice Husk > Craft Paper> Newspaper > Control.

3.8. Degradation Rate

The mulch made of craft paper degraded the fastest, going from 4 mm to 1.8 mm in thickness, at a rate of 55%. Craft paper mulch demonstrated a high degree of biodegradability, adding a significant amount of organic matter to the soil and assisting in moisture retention. The breakdown rate of the rice straw mulch was 51.67%. Because rice straw decomposes at a very rapid rate, it is a good choice for improving soil health and water retention. It was then followed by newspaper, the initial thickness of the newspaper mulch, 5 mm, was reduced to 2.5 mm by a degradation rate of 50% (Table 4). This means that during the research period, half of the newspaper mulch material broke down. When it comes to adding organic matter to the soil and promoting moisture retention, newspaper mulch might be regarded as being only somewhat successful. The black plastic mulch did not show a

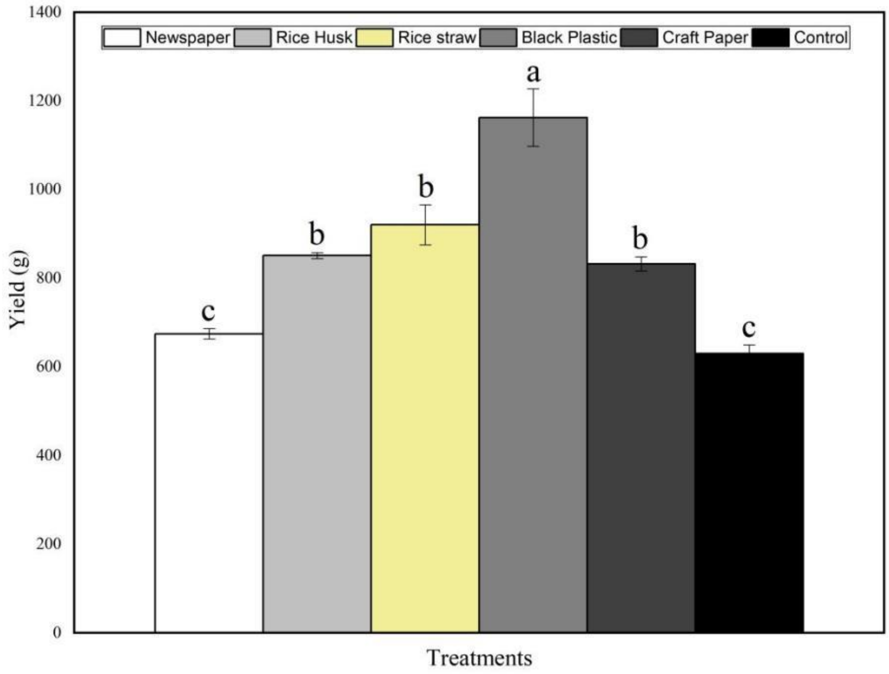

Figure 4. Cauliflower yield under various organic and plastic mulching treatments

Table 4. Impact of various mulch types on the pace of soil degradation in cauliflower

Treatments	Initial Thickness (mm)	Final Thickness (mm)	Degradation Rate (%)
Newspaper	5	2.5	50
Rice Husk	7	4.2	40
Rice Straw	6	2.9	51.7
Craft Paper	4	1.8	55
Black Plastic	2	2	-

degradation rate, maintaining its initial thickness of 2 mm, it has shown stability and resilience to decomposition, making it a long-lasting mulch alternative but not one that contributes much organic matter.

4. DISCUSSIONS

According to the study, black plastic mulch improves cauliflower development and productivity, making it the ideal mulching alternative. This mulch regulates soil temperature by absorbing and re-radiating solar energy, which is particularly beneficial during cooler months, promoting faster root development and overall plant growth (Job et al., 2018). Additionally, it conserves soil moisture by reducing evaporation, ensuring consistent moisture levels crucial for cauliflower. The mulch also suppresses weed growth by blocking sunlight, reducing competition for nutrients and water. Furthermore, as organic matter decomposes under the mulch, it releases essential nutrients like nitrogen, potassium, and calcium, enhancing nutrient availability (Demo & Asefa Bogale, 2024). These combined benefits lead to higher yields and better-quality produce, making black plastic mulch a preferred choice for farmers.

Black mulch film can also suppress the growth of weeds and reduce the occurrence of crop pests and diseases (Akhir & Mustapha, 2022). The maximum moisture content (46.3%), highest amounts of available potassium (35.2 mg Kg^{-1}), and significant improvements in soil temperature (37.6°C, and a 22.9% increase) were all achieved with black plastic mulch. Together, these components resulted in the study's best yield and healthiest plants.

While organic mulches like rice husk and rice straw offer certain benefits, their overall effectiveness falls short when compared to black plastic mulch. For instance, rice husk mulch significantly increased soil temperature by 26.7% and contained high levels of phosphorus (36.5 mg Kg^{-1}) and accessible nitrogen (22.4 mg Kg^{-1}). These attributes highlight the potential of rice husk mulch to enhance soil fertility through the rapid release of nutrients. However, despite these advantages, the overall plant performance under rice husk and rice straw mulch was inferior to that observed with black plastic mulch.

Bucki and Siwek (2019) stated that a factor that impedes the extensive use of organic mulches is the feasibility of serving them to the crop field and uniformly distributing them there. Moreover, many of these mulches decompose rapidly which demands regular renewal. In contrast, black plastic mulch excels in moisture retention and temperature control, creating a more stable and conducive environment for plant growth throughout the season. This disparity underscores the limitations of organic mulches in terms of long-term performance. While they improve soil fertility rapidly, their inability to maintain optimal soil moisture and temperature can hinder overall plant health and productivity. Therefore, for sustained plant performance, black plastic mulch proves to be a superior option despite the environmental concerns associated with plastic use.

Black plastic mulch greatly increases soil moisture retention and temperature regulation. The mulch's high moisture content (46.3%) is attributed to its capacity to limit weed growth, reducing water competition. This is supported by research indicating that black plastic mulch effectively conserves soil moisture by minimizing evaporation and maintaining consistent moisture levels, which are crucial for optimal plant growth (Job et al., 2018). Additionally, the mulch's ability to block sunlight prevents weed germination and growth, thereby reducing competition for water and nutrients. However, plastic film residues have a negative impact on long-term soil health especially the microplastic disrupts the soil structure which reduces water movement in the soil and decreases root absorption by plants (Sajjad et al., 2022; Yuanqiao et al., 2020). Additionally, water evaporating from the soil top condenses on the underside of the plastic mulch and drips back into the soil, keeping moisture levels high. The mulch also raises soil temperature by 22.9% by reducing conduction and convection losses and trapping longwave radiation from the ground. Warmer soil conditions boost microbial activity and nutrient availability, resulting in improved plant development.

Black plastic mulch significantly enhances the availability of potassium, an essential nutrient for plant growth, by increasing its concentration to 35.2 mg Kg^{-1}. This increase is primarily due to the expansion of the clay surface caused by the warmer soil temperatures beneath the mulch. Increased soil temperatures enhance the nutrients such as potassium from soil particles (Khangura et al., 2023). Additionally, the conditions created by black plastic mulch promote the production of organic acids and CO_2. According to Cabilovski et al. (2014), these organic acids form carbonic acid, which lowers the soil pH and increases nutrient solubility, thereby improving nutrient availability. This dual mechanism of temperature-induced nutrient release and acidification-driven solubility underscores the effectiveness of black plastic mulch in enhancing potassium availability for plant growth.

Newspaper and craft paper mulches have demonstrated an average rate of effectiveness in agricultural applications. While craft paper mulch significantly increases the amount of organic matter in the soil and helps retain moisture, it contributes little to the overall growth and yield of plants. This is likely due to its limited ability to regulate soil temperature and suppress weed growth compared to other mulching materials. Paper mulches have no disposal problems into the soil but their attribute or quality needs to be adjusted or adapted for mulching purposes in horticulture and agriculture (Haapala et al., 2014). In most cases, organic mulches have a positive effect on plant growth and yield, but not always. (Merfield, 2002) stated that organic mulches may possibly rob nitrogen from the soil when they are decomposed by microbes.

5. CONCLUSION

This study evaluated the effects of various organic and plastic mulches on soil properties, carbon sequestration, degradation, and cauliflower yield in Northern Bangladesh. Mulching treatments significantly enhanced soil properties and cauliflower yield compared to no-mulch treatment. Specifically, black plastic mulch significantly boosted soil temperature and moisture retention, while organic (rice husk and newspaper) mulches improved organic carbon, pH, and nutrient availability of soil. Organic mulch material, particularly rice husk, showed greater performance on carbon sequestration, enriching soil organic matter and improving moisture holding capacity, which potentially aids climate change mitigation. However, black plastic mulch delivered the highest cauliflower yield, followed by rice straw and husk materials. Finally, both organic and plastic mulches outperformed the control in multiple soil parameters, including pH, and availability of N, P, and K. However, considering the positive impact on yield, ease of use, and potential benefits on soil temperature modifications and water conservation, black plastic mulch appears to be a compelling option for cauliflower growers in Northern Bangladesh.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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