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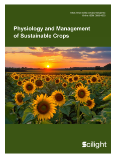

Article

Plastic Mulch as a Sustainable Yield-Boosting Strategy for Fresh Corn Production in the Andean Region of Ecuador

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Abstract: The use of plastic mulch is a promising agronomic technique for enhancing crop performance under challenging environmental conditions. Mulching is commonly employed in horticultural crops, providing benefits such as increased yields, effective weed control, soil moisture conservation, and elevated soil temperature. However, its advantages for Andean crops have been insufficiently studied. This research evaluated the impact of plastic mulch on fresh corn yield across 19 locations in the Sierra (highlands) of Ecuador over two production cycles (2022–2023 and 2023–2024). Results indicated that plastic mulching significantly increased yields compared to conventional planting methods, with mean increases of 55.06% in the first cycle and 66.27% in the second cycle. A meta-analysis of 28 field trials confirmed a strong and statistically significant overall yield effect of the mulch (Standardized mean difference = 1.62; $p < 0.0001$). Further analysis revealed that combining plastic mulch with improved maize varieties resulted in significantly higher yields (14.78 ± 0.56 $t \cdot ha^{-1}$) compared to local varieties (10.00 ± 0.74 $t \cdot ha^{-1}$), indicating a synergistic effect. Notably, reutilized plastic mulch performed comparably to new mulch, showing no statistically significant difference in yield, suggesting agronomic viability beyond one cycle. The profitability analysis demonstrated that reutilized plastic mulch provided the highest economic return (benefit/cost ratio of 1.76) and posed less economic risk compared to conventional planting. These findings indicate that plastic mulching can be both a profitable and environmentally responsible practice. In contrast, conventional management was associated with greater risk and occasional financial loss.

Keywords: Andean crops; climate resilience; corn yield; maize productivity; sustainable agriculture; meta-analysis; plastic reuse

1. Introduction

Corn or maize (*Zea mays* L.) is one of the most important crops in the Andean region, not only because of its economic relevance but also for its essential role in ensuring the food and nutritional security of rural communities [1–3]. In 2023, the area sown with floury maize (*Zea mays* var. *amylacea*) in Ecuador reached 59,441 hectares, with an average fresh corn yield of 3.41 t·ha^{-1} [4]. This figure is significantly lower than yields reported in Peru (9.98 t·ha^{-1}), Chile (14.22 t·ha^{-1}), and Mexico (15.61 t ha^{-1}) [5]. This productivity gap undermines rural livelihoods, intensifying poverty, food insecurity, and childhood malnutrition in the highlands.

Addressing these challenges is critical given the dual pressures of climate change and the projected rise in global food demand by 2050 [6] to increase maize productivity through innovative and sustainable agronomic practices. Among the strategies to improve yields, plastic mulching has shown promise. By covering the soil with plastic sheets, this technique conserves moisture, moderates' temperature, and suppresses weeds [7,8]. Widely adopted in China and South Korea, it has boosted yields across diverse crops [9–11]. In contrast, its use in Latin America—and particularly for Andean crops—remains scarce and largely unexplored [12].

Preliminary research in the Ecuadorian highlands indicates that plastic mulch can raise soil moisture in the upper 30 cm by up to 14.18%, increase soil temperature by 1.26 °C, and shorten the time to flowering in maize [13]. Sangoquiza et al. [14] further reported an 85% yield increase under mulching compared to conventional management (2.91 vs. 4.95 t·ha^{-1}) and a reduction in production costs from \$0.77 to \$0.67 kg^{-1}. However, these findings are limited by small sample sizes, restricted environments, and reliance on improved maize varieties.

In the Andean region, most smallholders continue to use local or creole seeds [2], whose response to mulching remains uncertain. Moreover, concerns about the environmental impact of plastic—particularly its disposal and recycling—persist. Reutilization of mulch across production cycles, however, could lessen these impacts [15]. Against this backdrop, this study aimed to evaluate the effects of plastic mulch on maize yield and profitability in the Ecuadorian highlands using both improved and local varieties, and to assess the performance of reutilized mulch over two consecutive production cycles. We hypothesized that plastic mulch, including its reutilization, improves yield and profitability for both seed types in these highland systems.

2. Materials and Methods

2.1. Site Description

Experimental plots for evaluating plastic mulching technology were established during the years 2022, 2023, and 2024 across 19 locations in the Ecuadorian highlands (Figure 1), at altitudes ranging from 2200 to 3100 m above sea level (Table 1). The climate in the Ecuadorian Andes varies considerably, with mean temperatures ranging from 8 °C to 20 °C depending on elevation and location (Supplementary Table S1 [16]). The predominant soil textures in the study areas include sandy, loam, and clay soils, with variations by province. In the first production cycle, improved maize seed was used in Gualaceo, Cojitambo, San Andrés, and Cutuglagua, while local seed varieties were employed in the remaining sites. For the second cycle, improved seed was used only in Gualaceo and Cutuglagua (Table 1).

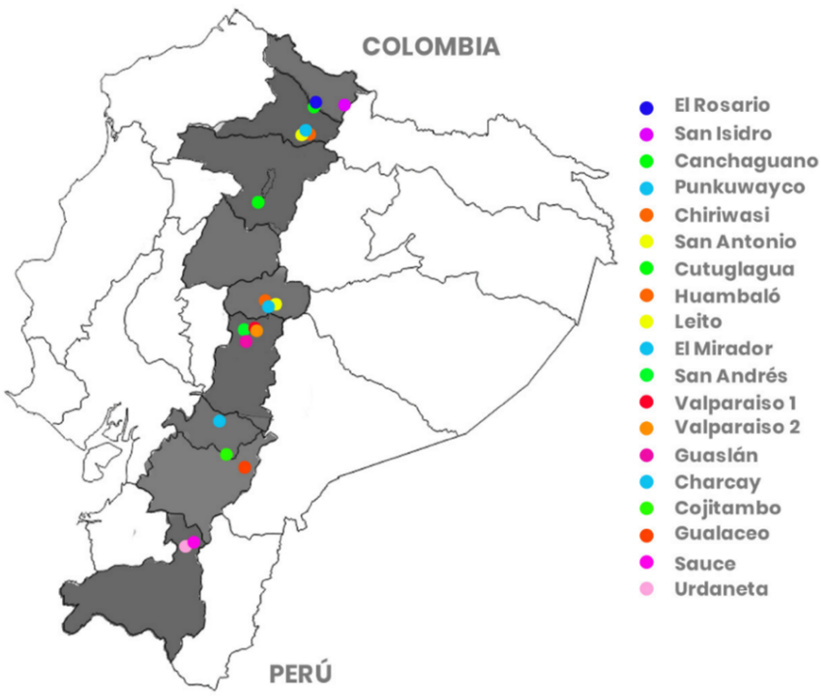

Figure 1. Site locations of 19 study sites in the Andean Region of Ecuador.

Table 1. Locations, altitude, soil texture, and planting details for maize cultivation trials in the Ecuadorian Highlands (Cycles 2022–2023 and 2023–2024).

Province	Location	Altitude (m a.s.l.)	Soil Texture Class	Cycle 1 (2022–2023)		Cycle 2 (2023–2024)	
				Planting Date	Seed Type	Planting Date	Seed Type
Loja	Urdaneta	2529	Clayey	01/11/2022	Local	Not planted	
	Sauce	2460	Sandy clay loam	08/12/2022	Local	29/11/2023	Local
Azuay	Gualaceo	2213	Clayey	27/09/2022	INIAP 103	01/11/2023	INIAP 103
Cañar	Cojitambo	2877	Clayey	31/10/2022	INIAP 103	Not planted	
	Charcay	2890	Sandy clay loam	06/01/2023	Local	19/10/2023	Local
Chimborazo	San Andrés	3100	Sandy	26/10/2022	INIAP 193	30/10/2023	Local
	Valparaíso 1	2795	Sandy	26/10/2022	Local	30/10/2023	Local
	Guaslán	2752	Sandy loam	24/03/2023	Local	31/10/2023	Local
	Valparaíso 2	2971	Sandy	18/04/2023	Local	30/11/2023	Local
Tungurahua	Huambaló	2956	Sandy loam	12/04/2022	Local	Not planted	
	Leito	2588	Sandy loam	13/06/2022	Local	22/06/2023	Local
	El Mirador	2750	Silty sand	11/05/2022	Local	12/04/2023	Local
Pichincha	Cutuglagua	3050	Silty loam	01/12/2022	INIAP 101	14/11/2023	INIAP 122
Imbabura	Punkuwayco	2496	Clayey	22/11/2022	Local	Not planted	
	Chiriwasi	2987	Clayey	02/12/2022	Local	Not planted	
	San Antonio	2631	Clay loam	22/11/2022	Local	Not planted	
Carchi	Canchaguano	2830	Clay loam	08/11/2022	Local	Not planted	
	San Isidro	2400	Clay loam	07/10/2022	Local	Not planted	
	El Rosario	2960	Clay loam	12/10/2022	Local	Not planted	

2.2. Experimental Design and Field Management

The study employed a randomized complete block design with three replicates and two treatments: plastic mulch and farmer-managed conventional planting (without mulch), which served as the control. Each plot had a surface area of 500 m^2. Sowing dates varied by location (Table 1), and planting followed the recommendations of Sangoquiza et al. [14], using raised beds 1.2 m wide with double rows spaced 0.4 m apart. Plants were spaced 0.6 m between rows and 0.25 m between plants, with two seeds sown per planting hole (Supplementary Figure S1). The plastic mulch comprised a 35-µm thick black polyethylene agricultural film, 1.4 m wide (Ginegar, manufactured in Israel). The farmer-managed conventional planting plot (control) reflected traditional management practices of farmers, with a row spacing of 0.8 m and 3–4 seeds sown every 0.5 m [2]. Thinning was conducted at the V3 vegetative stage: in mulched plots, one plant per site was retained, while in conventional plots, two plants per site were maintained, achieving a final plant density of 50,000 plants per hectare in both treatments.

In each location, both treatments were sown on the same day using the same seed type (improved or local) and received identical agronomic management, including fertilization and pest control. Crop management, carried out by the landowner farmer under the supervision of a field technician, ensured both proper crop care and the independence of the study. In locations where a second production cycle was evaluated (2023–2024), sowing was performed on the same site without removing the plastic or altering the raised beds (reutilized mulch). Only crop residues from the previous cycle were removed, taking care not to damage the mulch during plant removal. All treatments followed the same fertilization regime (120 kg·ha^{-1} N, 30 kg·ha^{-1} P, and 80 kg·ha^{-1}·K), applied 50% at planting and 50% at the V6 vegetative stage.

2.3. Sampling and Measurements

Fresh corn ears (choclo) were harvested at the R3 (milky) growth stage. In mulched plots, one bed with two rows (5 m each) was randomly selected, while in conventional plots, two 5-m rows were sampled for yield evaluation. Yield was determined by harvesting all ears from the net plot and weighing them on a digital scale. The weight was then converted to tons per hectare (t·ha^{-1}).

2.4. Statistical Analysis

All data were tabulated and analyzed using R software to compare yields between mulched and conventional plots. A meta-analysis was conducted using the *meta* package (version 8.1-0) for continuous outcome data (*metacont*) [17], applying the inverse-variance method. Heterogeneity was assessed using the restricted maximum-likelihood estimator for Tau-squared (τ^2), with the *Q*-profile method applied to generate confidence intervals for τ^2 and τ. The I^2 statistic was calculated based on the *Q*-test of heterogeneity [18]. *T*-tests ($p < 0.05$) were used to evaluate differences between production cycles (new vs. reutilized mulch) and seed types (improved vs. local).

2.5. Profitability Analysis

A benefit–cost analysis was conducted to assess the economic performance of maize production under mulching compared to conventional management. For each treatment and location, total production cost per hectare ($) was estimated from farmer-provided data, including expenses for labor, seeds, fertilizers, pest control, plastic film (if applicable), harvesting, and commercialization. Unit production cost ($\$\cdot kg^{-1}$) was obtained by dividing total cost by fresh yield ($t\cdot ha^{-1}$).

A nonlinear regression model (power function) was fitted for each production system to describe the inverse relationship between yield and unit cost. Model fit was evaluated using the coefficient of determination (R^2). Market-based profitability thresholds were established based on historical fresh corn prices in Ecuador for 2023 and 2024, ranging from a minimum of $0.28 kg^{-1} and a maximum of $0.73 kg^{-1} [19,20].

3. Results

3.1. Yield Performance Across Locations and Cycles

Plastic mulching consistently enhanced fresh corn yield across most of the 19 highland locations evaluated during two production cycles (2022–2023 and 2023–2024). In cycle 1, the average yield under plastic mulch was 12.56 $t\cdot ha^{-1}$, compared to 8.10 $t\cdot ha^{-1}$ in the conventional planting control, representing a mean yield increase of 55.06%. In cycle 2, with reutilized plastic mulch, the average yield was slightly lower at 11.04 $t\cdot ha^{-1}$), but still higher than the control yield of 6.64 $t\cdot ha^{-1}$), with a mean increase of 66.27% (Table 2). Nine of the nineteen locations did not undergo a second evaluation cycle due to significant damage to the plastic mulch caused by improper handling by the farmers. San Andrés did not present data from the first cycle because corn was harvested dry.

Yield response to plastic mulch varied significantly across locations and elevations. Notably, San Isidro (2960 m), Punkuwayco (2496 m), and Cutuglahua (3050 m) exhibited exceptional increases in yield, all exceeding 249%, with San Isidro achieving a remarkable 324.77%. In contrast, Huambaló demonstrated a negative yield response (−5.55%) in cycle 1, while Sauce showed a yield decline under mulch in cycle 2 (−19.65%), indicating that site-specific factors may influence the effectiveness of mulching. Yield increases varied significantly across locations and years in both the plastic mulching and conventional control plots (Table 2), highlighting the differences in environmental conditions and management practices among farmers in the highlands of Ecuador.

3.2. Meta-Analysis for Yield

A meta-analysis of 28 independent trials conducted over two years in 19 locations confirmed the overall efficacy of plastic mulching. The common or fixed effect model yielded a standardized mean difference (SMD) of 1.48, indicating how much the treatment or intervention differed from the control group in terms of standard deviations. This suggests a medium to large effect size between the yields from plastic mulch and those from conventional planting used as a control. The 95% confidence interval (CI) (0.98–1.98) did not cross zero, indicating that the effect was statistically significant ($p < 0.0001$). The random effects model showed an even higher SMD of 1.62 (95% CI: 1.05–2.19; $p < 0.0001$), indicating a stronger overall effect when accounting for variability between studies (Figure 2). The *z*-values in both models indicate that the effect is far from zero, further supporting the notion that the yield increase associated with plastic mulch is real and not due to random chance (Table 3).

Table 2. Mean and standard error of fresh corn yield with plastic mulch and conventional planting control across 19 locations and 28 trials in the highlands of Ecuador during two production cycles (*n* = 3).

Province	Location/Altitude (m a.s.l.)	Cycle 1 (2022-2023)			Cycle 2 (2023–2024)		
		Plastic Mulch ($t{\cdot}ha^{-1}$)	Conventional Control ($t{\cdot}ha^{-1}$)	Yield Increase (%)	Plastic Mulch ($t{\cdot}ha^{-1}$)	Conventional Control ($t{\cdot}ha^{-1}$)	Yield Increase (%)
Loja	Sauce/2460	10.88 ± 0.69	8.94 ± 0.39	21.70	6.38 ± 0.63	7.94 ± 0.82	−19.65
	Urdaneta/2529	8.86 ± 0.82	5.64 ± 0.61	57.09			
Cañar	Charcay/2888	11.33 ± 1.04	9.73 ± 0.58	16.44	8.76 ± 1.11	5.4 ± 0.64	62.22
	Cojitambo/2877	15.17 ± 1.61	7.98 ± 0.68	90.10			
Azuay	Gualaceo/2213	16.35 ± 0.53	16.00 ± 0.33	2.19	14.65 ± 1.36	11.65 ± 0.96	25.75
Chimborazo	Guaslán/2752	17.37 ± 1.58	15.67 ± 0.89	10.85	12.58 ± 0.05	4.73 ± 0.63	165.96
	Valparaíso 1/2794	7.16 ± 1.58	3.05 ± 0.72	134.75	6.17 ± 1.20	3.28 ± 0.79	88.11
	Valparaíso 2/2794	8.47 ± 0.08	5.25 ± 0.29	61.33	10.54 ± 0.04	9.00 ± 0.38	17.11
	San Andrés/3133				8.71 ± 0.72	2.24 ± 0.15	288.84
Tungurahua	El Mirador/2750	2.54 ± 0.16	1.51 ± 0.06	68.87	13.43 ± 0.27	6.48 ± 1.41	107.25
	Huambaló/2956	16.35 ± 1.81	17.31 ± 1.04	-5.55			
	Leito/2588	17.74 ± 0.72	9.35 ± 1.48	89.73	16.57 ± 0.43	8.04 ± 0.09	106.09
Pichincha	Cutuglagua/3050	15.41 ± 0.98	4.41 ± 0.69	249.43	12.71 ± 0.59	7.62 ± 0.89	66.80
Imbabura	Chirihuasi/2987	2.66 ± 0.17	1.77 ± 0.22	50.28			
	Punkuwayco/2496	6.97 ± 0.89	1.56 ± 0.01	346.79			
Carchi	San Antonio/2631	24.60 ± 1.32	22.10 ± 0.89	11.31			
	Canchaguano/2213	22.65 ± 4.04	9.81 ± 1.18	130.89			
	El Rosario/2400	3.78 ± 0.76	1.35 ± 0.13	180.74			
	San Isidro/2960	18.52 ± 2.02	4.36 ± 0.26	324.77			
Mean		12.56	8.10	55.06	11.04	6.64	66.27

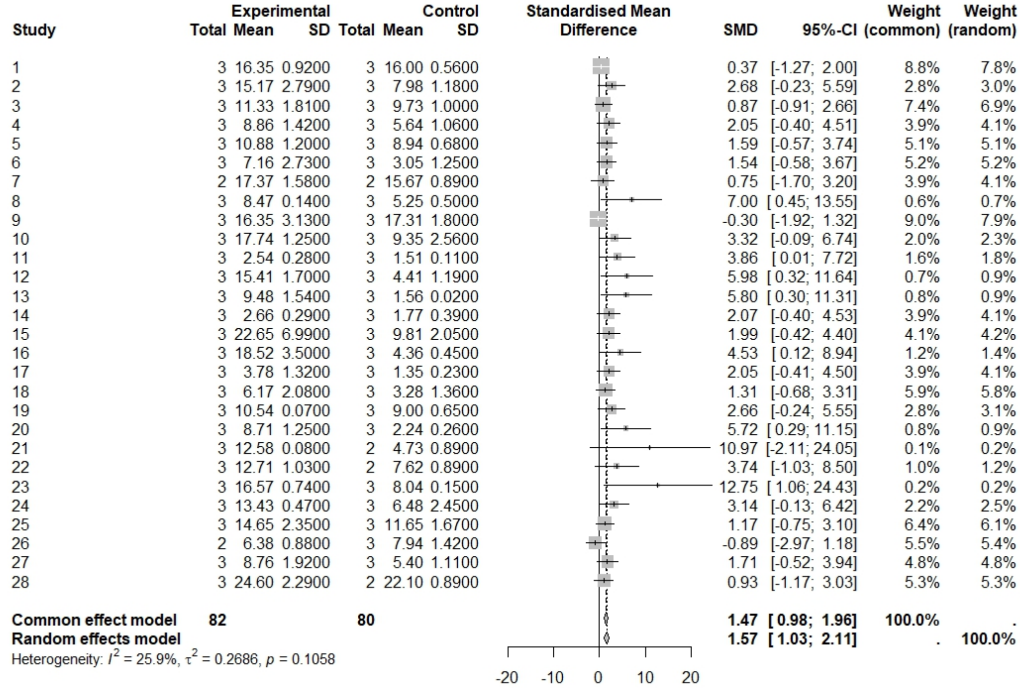

Figure 2. Forest plot illustrating the effect of experimental plastic mulch vs. conventional planting control on fresh corn yield in 28 studies conducted in the highlands of Ecuador between 2022 and 2024 (SD = standard deviation; SMD = standardized mean difference; CI = confidence interval).

Table 3. Standardized mean difference (SMD) and test of heterogeneity in a meta-analysis using fixed and random effects models to estimate true differences between plastic mulching and conventional planting from 28 trials conducted in the highlands of Ecuador for 2022–2024.

Model	SMD	Confidence Interval 95%	*Z* Value	*p* Value
Common effect model	1.4825	[0.9811; 1.9840]	5.79	<0.0001
Random effects model	1.6166	[1.0456; 2.1876]	5.55	<0.0001
Test of Heterogeneity				
Tau-squared (τ^2)	0.2686	[0.0000; 5.1700]		-
Tau (τ)	0.5182	[0.0000; 2.738]		-
I-squared (I^2)	25.90%	[0.0%; 53.6%]		-
Q-Test	35.35			0.1058

The meta-analysis results provided insight into the level of heterogeneity among the included studies (Table 3). The tau-squared (τ^2) of 0.2686 represented the variance of the true effect sizes across studies, quantifying the amount of between-study variance. The tau (τ) indicated that the standard deviation of the true effect sizes across studies was 0.5182, with a 95% confidence interval ranging from 0 to 2.738. The *I*-squared (I^2) value of 25.90 suggested moderate heterogeneity, indicating that approximately 26% of the variation in effect sizes is attributable to differences between studies, while the remaining 74% is due to random variation within studies. The 95% confidence interval for I^2 [0.0%; 54.6%] reflected the uncertainty surrounding this estimate, spanning from very little to moderate heterogeneity. The *p*-value from the test of heterogeneity (*Q*-test) was 0.1058, which exceeds the conventional significance threshold of 0.05, indicating that the observed heterogeneity across studies was not statistically significant.

3.3. Comparison between Production Cycles and Seed Types

Table 4 examined the effects of new versus reutilized mulch and seed type on yield performance. New mulch in cycle 1 significantly outperformed conventional planting (11.92 vs. 8.21 t·ha^{-1}; $p = 0.0033$), while reutilized mulch maintained a significant yield advantage (11.31 vs. 7.12 t·ha^{-1}; $p < 0.0001$) in cycle 2. The comparison between cycles revealed no significant difference between new and reutilized mulch treatments (11.92 vs. 11.31 t·ha^{-1}; $p = 0.9444$), suggesting that reutilized mulch remains agronomically viable under highland conditions.

Table 4. Effect of new and reutilized plastic mulch and seed type on fresh corn yield in the Ecuadorian highlands. The mean and standard error of the mean are shown.

Treatments Plastic	Fresh Corn Yield ($t \cdot ha^{-1}$)		*T* Test
	Plastic Mulch	Conventional Control	*p* Value
New, cycle 1(year 2022–2023)	11.92 ± 1.03	8.21 ± 0.93	0.0033
Reutilized, cycle 2 (year 2023–2024)	11.31 ± 0.79	7.12 ± 0.64	<0.0001
T test (*p* value)	0.9444	0.4872	-
Type of seed			
Improved seed	14.78 ± 0.56	9.62 ± 1.69	0.0091
Local landrace seed	10.00 ± 0.74	6.50 ± 0.50	<0.0001
T test (*p* value)	<0.0001	0.0093	-

Seed type also influenced fresh corn yield outcomes. Improved or bred varieties achieved significantly higher yields under plastic mulch (14.78 ± 0.56 $t \cdot ha^{-1}$) compared to local landraces (10.00 ± 0.74 $t \cdot ha^{-1}$), with both outperformed their respective controls ($p < 0.01$) (Table 4). This suggests a synergistic effect when combining plastic mulching with genetically improved seed material.

3.4. Profitability Analysis

The economic analysis of 28 trials in the Ecuadorian highlands showed that plastic mulching consistently improved the profitability of fresh corn production compared to conventional management. On average, the benefit–cost ratio (B/C) under mulch increased from 1.36 in the first cycle (2022–2023) to 1.76 in the second cycle (2023–2024), while conventional management showed less economic benefit. The average production cost per kilogram decreased from \$0.36 kg^{-1} in the first cycle to \$0.21 kg^{-1} in the second cycle under plastic mulch, while conventional planting had higher production cost, from \$ 0.47 USD kg^{-1} in the first cycle to \$0.27 kg^{-1} in the second cycle (Table 5).

In the first cycle, plastic mulch raised production costs by 65%, but this was offset by an average yield increase of 55.06%, resulting in a B/C ratio slightly (2%) higher than that of conventional management. By the second cycle, with mulch reutilized, the B/C ratio was 22% higher than that of the conventional system, reflecting improved efficiency. Across both years, mulching was profitable (B/C > 1.0) in 71% of plots (20 of 28), compared with 61% (17 of 28) under conventional management (Table 5).

Considering the strong seasonal variability in fresh corn prices, higher yields were closely associated with lower production costs per kilogram. Market prices in 2023 and 2024 ranged from \$0.28 to \$0.73 kg^{-1} [19,20]. Within this range, 7% of mulched plots (2 of 28) and 14% of conventional plots (4 of 28) were unprofitable when production costs exceeded \$0.73 kg^{-1} (Figure 3). Conversely, at the lower threshold (below \$0.28 kg^{-1}), mulching remained profitable in 68% of plots (19 of 28), compared with 54% (15 of 28) for conventional management. Overall, these results demonstrate that plastic mulching—Especially when reutilized in successive cycles—Not only enhances economic returns but also provides greater resilience to market price fluctuations, thereby reducing production risks for smallholders.

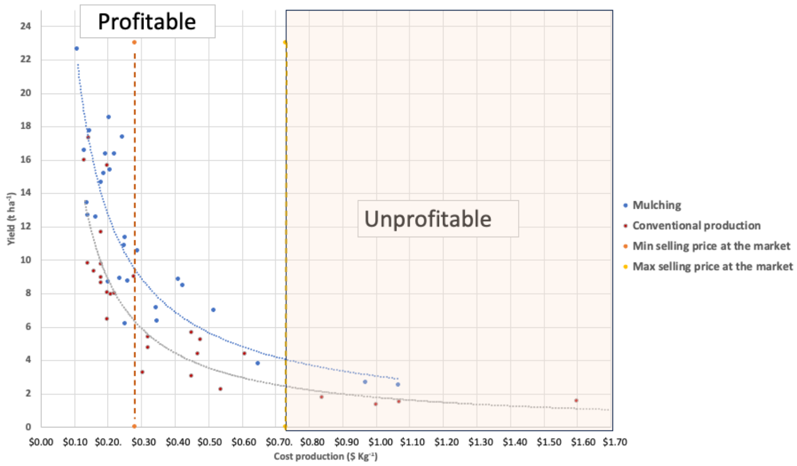

Figure 3. Relationship between fresh corn yield ($t\ ha^{-1}$) and production cost (\$ kg^{-1}) under plastic mulching and conventional systems. Vertical dashed lines indicate economic thresholds based on local market prices from 2022–2023: minimum \$0.28 kg^{-1} and maximum \$0.73 kg^{-1}. Data points to the left of these thresholds represent economically viable (profitable) plots, while those to the right represent non-viable (unprofitable) plots.

Table 5. Production Cost and Benefit-Cost Ratio of fresh corn produced with plastic mulching and conventional management (control) across two evaluation cycles (2022–2023 and 2023–2024) in 19 locations and 28 trials in the Ecuadorian Highlands.

Province	Location	Cycle 1 (2022-2023)								Cycle 2 (2023–2024)							
		Plastic mulch				Conventional Control				Plastic Mulch				Conventional Control			
		Prod. Cost $\$\ kg^{-1}$	Total Cost $\$\ ha^{-1}$	Gross Income $\$\ ha^{-1}$	Benefit /cost	Prod. Cost $\$\ kg^{-1}$	Total Cost $\$\ ha^{-1}$	Gross Income $\$\ ha^{-1}$	Benefit /cost	Prod. Cost $\$\ kg^{-1}$	Total Cost $\$\ ha^{-1}$	Gross Income $\$\ ha^{-1}$	Benefit /cost	Prod. Cost $\$\ kg^{-1}$	Total Cost $\$\ ha^{-1}$	Gross Income $\$\ ha^{-1}$	Benefit/ cost
Loja	Sauce	0.25	2720	3627	1.33	0.18	1609	2980	1.85	0.35	2233	2127	0.95	0.21	1667	2647	1.59
	Urdaneta	0.41	3633	2953	0.81	0.45	2538	1880	0.74								
Cañar	Charcay	0.25	2833	3777	1.33	0.18	1751	3243	1.85	0.26	2278	2920	1.28	0.32	1728	1800	1.04
	Cojitambo	0.19	2882	5057	1.75	0.22	1756	2660	1.52								
Azuay	Gualaceo	0.19	3107	5450	1.75	0.13	2080	5333	2.56	0.18	2637	4883	1.85	0.18	2097	3883	1.85
Chimborazo	Guaslán	0.24	4169	5790	1.39	0.20	3134	5223	1.67	0.16	2013	4193	2.08	0.32	1514	1577	1.04
	Valparaíso 1	0.35	2506	2387	0.95	0.45	1373	1017	0.74	0.25	1543	2057	1.33	0.31	1017	1093	1.08
	Valparaíso 2	0.42	3557	2823	0.79	0.48	2520	1750	0.69	0.29	3057	3513	1.15	0.28	2520	3000	1.19
	San Andrés									0.20	1742	2903	1.67	0.54	1210	747	
Tungurahua	El Mirador	1.07	2675	833	0.31	1.07	1616	503	0.31	0.14	1880	4477	2.38	0.20	1296	2160	1.67
	Huambaló	0.22	3597	5450	1.52	0.14	2423	5770	2.38								
	Leito	0.15	2661	5913	2.22	0.16	1496	3117	2.08	0.13	2154	5523	2.56	0.20	1608	2680	1.67
Pichincha	Cutuglagua	0.21	3236	5137	1.59	0.47	2073	1470	0.71	0.14	1779	4237	2.38	0.18	1372	2540	1.85
Imbabura	Chirihuasi	0.97	2580	887	0.34	0.84	1487	590	0.40								
	Punkuwayco	0.52	3624	2323	0.64	1.60	2496	520	0.21								
	San Antonio	0.13	3198	8200	2.56	0.11	2431	7367	3.03								
Carchi	Canchaguano	0.11	2492	7550	3.03	0.14	1373	3270	2.38								
	El Rosario	0.65	2464	1263	0.51	1.00	1350	450	0.33								
	San Isidro	0.20	3704	6173	1.67	0.61	2660	1453	0.55								
Mean		0.36	3091	4200	1.36	0.47	2009	2700	1.33	0.21	2132	3683	1.76	0.27	1603	2213	1.44

4. Discussion

Developing and adapting agricultural technologies that increase yield and reduce vulnerability to climate change is essential for addressing global food security challenges. As climate change intensifies, unpredictable weather patterns—such as droughts and floods—make conventional farming methods increasingly unreliable, putting already vulnerable populations at greater risk. By investing in agricultural innovations, it is possible to reduce the yield gap and enable farmers to produce more food on the same land, thereby strengthening resilience to climate shocks and supporting a more stable and sustainable food supply.

The findings of this study show that plastic mulching significantly improves fresh corn yield across multiple sites in the Ecuadorian highlands over two production cycles, with an average yield gain of 61%. These results are consistent with previous studies reporting yield improvements of 162% [13], 27% [21], and within 19–48% [22] attributed to plastic mulching.

In the Ecuadorian highlands, characterized by altitudes of 2200–3100 m above sea level and average temperatures of 8–20 °C, the benefits of plastic mulching are likely linked to increased soil temperature, reduced evapotranspiration, and greater moisture retention, as reported previously [13,23,24]. Notably, the highest yield gains were observed in cooler, higher-altitude locations such as San Isidro, Cutuglagua, and Guaslán, supporting the argument that mulching moderates the microclimate and promotes plant growth and vigor [25,26]. However, responses varied across sites (Table 2), indicating that both climatic factors and management practices strongly influence outcomes. For example, in Huambaló and Sauce, mulching did not consistently outperform conventional methods, possibly due to low solar radiation, excess moisture, or management-related issues, as also noted by Cai et al. [21] and Wang et al. [23].

A synergistic effect between mulching and seed type was also observed, with improved varieties yielding more than local ones (Table 4). This advantage likely stems from genetic selection and breeding that enhance both productivity and adaptation to local agroecological conditions [27]. The combination of improved varieties and the microclimate buffering effect of mulch appears to amplify yield gains. Similarly, Wu et al. [9] reported that mulching improves plant attributes such as yield and water-use efficiency, suggesting that optimized conditions allow hybrids to better express their genetic potential.

From an economic standpoint, plastic mulching increased production costs by an average of 65% in the first cultivation cycle. However, this was offset by substantially higher revenues from yield gains. Reutilizing mulch in the second cycle resulted in the highest average benefit–cost ratio (1.76), outperforming conventional management and indicating stronger economic efficiency. By contrast, conventional practices showed high variability in benefit–cost ratios, with some cases reflecting negative profitability, highlighting greater economic risk. Although mulching was generally profitable, variability among sites underscores the influence of local factors on economic outcomes (Table 5). Extending mulch use beyond a single cycle is therefore recommended, as reutilization stabilized profitability by reducing input variability—particularly costs related to plastic acquisition, labor, and machinery—while maintaining yield performance (Table 4). These findings are consistent with Liu et al. [15], who demonstrated comparable yields between reutilized and new mulch, confirming both the technical feasibility and the economic advantages of reutilization in highland systems.

From a sustainability perspective, results suggest that plastic mulching, particularly when reutilized, reduces the risks and uncertainties of conventional management, enhances productivity, and lowers production costs. Reutilizing plastic mulch in crop rotation systems—especially with short-cycle legumes—could further improve efficiency by enhancing soil fertility, diversifying income, and extending the utility of mulch. Studies in other regions have shown that maize–legume rotations under mulching improve soil fertility and increase subsequent maize yields [28–30]. Zhang et al. [31] further noted that reutilized plastic mulch can be both more profitable and environmentally favorable than new mulch if its physical integrity is maintained. Incorporating plastic mulch into corn–faba bean rotations, for example, increased net income by 13%. However, in the Andean region, further research is needed to evaluate the feasibility and benefits of these systems.

This study demonstrates that plastic mulching is a robust agronomic practice for enhancing maize productivity in the Ecuadorian highlands. The technology appears especially beneficial at higher altitudes and under cooler or less favorable conditions. Combining mulching with high-yielding cultivars further amplifies production gains, offering a viable pathway toward improved food security and agricultural profitability in mountainous regions. Moreover, the use of reutilized mulch represents not only an environmentally responsible practice but also an economically viable alternative for farmers in the Ecuadorian highlands. Yet, widespread adoption among smallholders will depend on access to credit, technical training, and farmer awareness of the benefits of plastic mulching, and farmers' perceptions of the technology's profitability and sustainability benefits.

Institutional support through training programs, financing mechanisms, and extension services will be crucial to scaling adoption.

Environmental concerns regarding plastic use remain important. Current research is focused on biodegradable alternatives and more efficient recycling strategies. Soil-biodegradable mulches are being developed to meet performance and end-of-life standards (e.g., EN 17033 and ISO 23517), allowing incorporation into soil without adverse ecological impacts [32]. At the same time, recycling innovations are targeting better collection and cleaning systems, along with catalytic upcycling pathways, to improve recovery and reuse of agricultural plastics [33]. These advances are expected to support long-term adoption and sustainability of mulching practices.

5. Conclusions

This study shows that plastic mulching is an effective and sustainable strategy for increasing fresh corn yields in the Ecuadorian highlands. Across two cycles and 19 locations, plastic mulch consistently outperformed conventional planting, with average yield gains of 55.06% in the first cycle and 66.27% in the second when mulch was reutilized. Plastic mulching also enhanced profitability, particularly when reutilized, underscoring both its economic and environmental advantages.

Overall, plastic mulching represents a climate-resilient, scalable, and profitable technology aligned with sustainable intensification goals for highland maize systems. Future research should examine long-term impacts, evaluate biodegradable alternatives, and assess economic feasibility for broader adoption in Andean Cropping systems. Institutional policies that promote training, financing, and extension services will be essential to scaling the practice. As global food demand continues to rise, such innovations will be critical for meeting future needs while adapting to rapidly changing environmental conditions.

Supplementary Materials

The additional data and information can be downloaded at https://media.sciltp.com/articles/others/2509041606508249/PMSC-2508000034-Supplementary-FC-done.pdf.

Author Contributions

A.P.-V.: wrote the article, performed the economic analysis, and consolidated and analyzed the data; J.L.Z.-M.: designed and led the study, performed statistical analysis, and wrote the manuscript; C.S.-G. and C.S.-C.: participated in the design, implementation, analysis, and discussion of data; R.M.-T., C.A.-I., M.N.-B., V.L.-G., J.C.-V., J.S.-S., and R.G.-C. carried out the implementation of the trials, farm monitoring, and evaluation of the manuscript; R.G.-C.: participated in the data analysis and in the writing of the article; C.H.P.: participated in the study design and discussion of results. All authors have read and agreed to the published version of the manuscript.

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Not applicable.

Data Availability Statement

Data will be available upon request to the corresponding author.

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Conflicts of Interest

The authors declare no conflict of interest.

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