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Environmental-Friendly Agricultural Practices and Soil Conservation: A Case Study of Herbicides Use in the Gayo Highlands

Raichan Izzati[1,2,3], Abubakar Karim[2,3], Hifnalisa[2,3], Hasanuddin[4*]

[1] Doctoral Program of Agricultural Sciences, Postgraduate School, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia
[2] Center for Aceh Coffee and Cocoa Research, Research and Community Service Institution, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia
[3] Soil Science Department, Faculty of Agriculture, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia
[4] Agrotechnology Department, Faculty of Agriculture, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia

Corresponding Author Email: hasanuddin@usk.ac.id

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ABSTRACT

Results from International Laboratory Research indicate that Gayo Arabica coffee contains glyphosate chemical residues that exceed permissible limits. Specifically, glyphosate residues were found to exceed the maximum limit of 0.1 mg/kg, as set by the WHO/FAO. The implementation of environmentally friendly agricultural practices is essential to promote soil health. This investigation represents the first systematic study utilizing a stratified random sampling questionnaire. This study aims to identify the distribution, active ingredients, dosage, and regulation of herbicide use in the Gayo Highlands region, covering 81,541.38 hectares. In this study, 101 out of 200 Arabica coffee farmers were found to use herbicides, with two types of active ingredients and 22 commercial brands, each with varying concentrations and application regulations. Notably, glyphosate was the most commonly used active ingredient, represented by 18 different commercial brands.

1. INTRODUCTION

The cultivation of Arabica coffee in the Gayo Highlands (DTG) has been a vital component of the local economy for many years. However, the use of chemicals, particularly herbicides, has become a growing concern both nationally and internationally. Given the increasing global concerns about pesticide residues in food, this study aims to assess the distribution and regulation of herbicide use in the Gayo Highlands region to ensure compliance with international pesticide residue standards and improve food safety. The region's abundant natural resources, including its fertile volcanic soil and heavy rainfall, create an ideal environment for Arabica coffee cultivation. Nevertheless, the need to manage the rampant weed growth in coffee plantations has led many farmers to depend heavily on herbicides, particularly those containing glyphosate.

Previous research has revealed that some Arabica coffee farms rely on chemical methods, particularly herbicides, to manage weed growth. The use of herbicides is especially favored in large-scale agricultural areas and young Arabica coffee plantations, as it is more efficient in eliminating and controlling weeds. Moreover, herbicides offer the advantage of reducing both time and labor costs for farmers. In fact, field data shows that nearly 50% of the expenses incurred by farmers for manual weed control could be saved by switching to herbicide application.

The Gayo Highlands experience high rainfall, making the use of agrochemicals, particularly herbicides, in Arabica coffee plantations unavoidable. Weed control is implemented to minimize the negative impacts of weeds, such as competition for nutrients, water, and light, production of growth-inhibiting compounds (allelopathy), serving as hosts for plant pests (insect pests or disease pathogens), and reducing product quality due to contamination from weed parts [1, 2]. Herbicides are widely used by farmers to manage weeds, especially in young coffee plantations [3]. Furthermore, the use of herbicides poses a challenge to maintaining the viability of organic coffee, potentially leading to rejection by buyers in the European market.

The rejection of Gayo Arabica coffee by several buyers in Europe has raised concerns in the coffee market. The reasons cited for this rejection are serious, stemming from research conducted by international laboratories indicating that Gayo Arabica coffee contains residues of the herbicide glyphosate that exceeds permissible limits. Countries in the Global North have imposed stricter requirements for food products imported into their markets. For instance, on November 13, 2020, the European Commission introduced acceptable residue levels for several chemicals commonly used for weeding control in agricultural products, set at 0.01 mg kg^{-1} or 0.01 ppm. This requirement applies to all agricultural products, including those managed conventionally as well as certified organic products [4].

This study was conducted in response to the issue, aiming to provide a clearer understanding of the distribution of herbicide use in smallholder Arabica coffee plantations in the Gayo Highlands. Additionally, the research seeks to assess farmers' awareness of herbicide usage in accordance with existing regulations and its impact on the sustainability of coffee production in the region. By understanding herbicide usage patterns and identifying the active ingredients employed by farmers in their plantations, it is hoped that more environmentally friendly solutions can be implemented to protect soil quality and ensure the long-term viability of Arabica coffee in Gayo. The findings of this study will provide critical insight into the region, with implications for improving policies regarding sustainable agricultural practices, enhancing environmental protection, and supporting the long-term economic viability of the Gayo Arabica coffee industry.

Figure 1 shows the chemical structure of glyphosate (N-(phosphonomethyl)glycine), which we aim to highlight as the structure of glyphosate. Farmers in the Gayo Highlands generally prefer using glyphosate as their herbicide of choice. This preference is largely due to glyphosate's rapid translocation mechanism [5]. Classified as a non-selective herbicide, glyphosate is effective in controlling all types of weeds [6]. Its mechanism of action involves inhibiting the activity of an enzyme called 5-enol-pyruvyl-shikimate-3-phosphate synthase (EPSPS) [7-10]. The inhibition of this enzyme prevents the biosynthesis of aromatic amino acids, specifically phenylalanine, tyrosine, and tryptophan [11]. Weeds treated with glyphosate herbicide typically die within one to three weeks. However, literature studies have identified that glyphosate can alter natural ecosystems by affecting various components of the soil and water microbial communities that sustain the balance of these ecosystems [12].

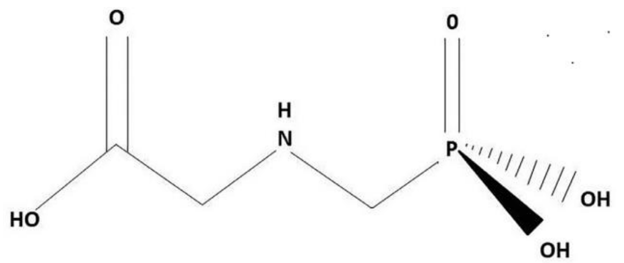

Figure 1. Chemical structure of glyphosate (N-(phosphonomethyl)glycine)

Several studies on the use of glyphosate have been reported. Research findings have shown that glyphosate has been detected in soil, plant products, and other living organisms that consume plant products, as well as in humans, water, and various organisms [13]. Significant concerns include effects on plant health, impacts on plant-nutrient interactions, and resistance in the environment. In 2016, in Finland glyphosate accounted for 67% of all herbicides active ingredients sold [14]. In Brazil, glyphosate is the most widely used active component in plantations, with 173,150.75 tons of the active ingredient (including its salts) recorded in 2017. These compounds are classified as ready-to-use products [15]. Like in other countries, glyphosate is the most widely used herbicide in Taiwan [16]. Research in Portugal indicated that symptoms of glyphosate poisoning in the third variety of coffee plants included chlorosis and leaf narrowing. Additionally, a decrease in the levels of N, P, K, Cu, and Mn was observed in coffee plants treated with glyphosate [17]. Studies have detected glyphosate in human blood and urine samples, indicating human exposure and its persistence in the organism [15].

In humans, the consumption of glyphosate-contaminated plant products may pose a potential carcinogenic risk, meaning they could contribute to the growth of cancer cells [18, 19]. The widespread presence of glyphosate and its metabolite, Amino-Methylphosphonic Acid (AMPA), in the environment, along with glyphosate's current classification as a potential carcinogen, necessitates degradation measures [20]. In aquatic environments, the presence of glyphosate molecules in water can impact aquatic organisms [21]. In soil, glyphosate can disrupt soil microbial ecology and affect soil enzyme activity [22-25]. Microorganisms are crucial for carbon and nutrient cycling, so changes in their presence and structure can impact higher trophic levels, thereby affecting the overall system [26].

In an effort to understand and address this situation, this research was conducted through a systematic investigation utilizing a questionnaire developed via stratified random sampling methods. The objective is to identify the distribution of herbicide use, types of active ingredients, dosages, and application frequency, including how often farmers spray herbicides on Arabica coffee plantations in the Gayo Highlands, covering an area of 81,541.38 hectares. This study provides critical insights into agricultural practices in the region and underscores the necessity for implementing more environmentally friendly farming methods to support soil health and the sustainability of coffee production.

2. RESEARCH METHODS

2.1 Observation of herbicide usage patterns

The study employed stratified random sampling to understand the herbicide usage patterns among Arabica coffee farmers in the Gayo Highlands region. The first step in the sampling process involved selecting district known for Arabica coffee production. All districts with Arabica coffee plantations in the region were included in the sampling frame. The sample was then stratified based on two main criteria: region and elevation. The stratification by region aimed to cover districts with significant Arabica coffee cultivation potential, while the stratification by elevation was done to identify possible differences in herbicide usage patterns influenced by environmental factors, such as altitude.

After the districts were selected, villages serving as the primary sites for Arabica coffee cultivation were proportionally chosen, with 10% of villages selected from each district. Subsequently, 10% of farmers using herbicides in their agricultural practices were chosen proportionally based on elevation to ensure fair representation across different altitude zones. Data collection was conducted in three major areas of the Gayo Highlands: Bener Meriah District, Aceh Tengah District, and Gayo Lues District, covering a total of several villages and districts that were representative of each elevation zone.

2.2 Mapping of herbicide usage distribution

The materials used in this study include existing maps of Arabica coffee plantations, soil type maps, elevation maps for each district in the Gayo Highlands, Global Positioning System (GPS) technology, and a questionnaire on the herbicide usage patterns among coffee farmers in the Gayo Highlands.

The survey of all sample farmers, conducted using a questionnaire, included 200 observed farmers, of whom 170 were successfully interviewed. The questionnaire comprised a total of six sections as follows: (1) personal data of the sample farmers, (2) characteristics of the farmers/village heads/community leaders, (3) components of coffee plantation cultivation, (4) agrochemical dimensions, (5) dimensions of household waste management, and (6) regulatory dimensions. Meanwhile, data analysis regarding the information included four components: (1) mapping of herbicide usage practices by farmers, (2) identification of herbicides used by farmers, (3) identification of herbicide dosages applied by farmers, and (4) identification of the timing and frequency of herbicide applications conducted by farmers throughout the year.

2.3 Data analysis

The data collected through the questionnaire were subsequently analyzed statistically, and the recorded coordinates were translated to determine the distribution of herbicide usage in the Gayo Highlands.

3. RESULT AND DISCUSSION

3.1 The area of existing arabica coffee (Sample location)

Table 1. Area of existing arabica coffee by subdistrict in the Gayo Highlands (DTG)

Regency	No.	Subdistrict	Area (ha)	Percentage (%)
Regency: Central Aceh	1.	Atu Lintang	3,744.52	9.13
	2.	Bebesan	1,252.58	3.05
	3.	Bies	851.64	2.08
	4.	Bintang	2,498.58	6.09
	5.	Celala	3,076.53	7.50
	6.	Jagong Jeget	4,503.24	10.98
	7.	Kebayakan	1,442.78	3.52
	8.	Ketol	6,910.99	16.84
	9.	Kute Panang	1,464.91	3.57
	10.	Linge	1,728.09	4.21
	11.	Lut Tawar	679.28	1.66
	12.	Pegasing	4,370.60	10.65
	13.	Rusip Antara	4,222.11	10.29
	14.	Silih Nara	4,281.21	10.44
		Total	**41,027.06**	**100**
Regency: Bener Meriah	1.	Bukit	3,126.21	8,93
	2.	Gajah Putih	1,153.24	3,30
	3.	Mesidah	2,423.86	6,93
	4.	Permata	19,719.00	56,36
	5.	Pintu Rime Gayo	4,446.67	12,71
	6.	Syiah Utama	50.56	0,14
	7.	Timang Gajah	2,422.12	6,92
	8.	Wih Pesam	1,648.37	4,71
		Total	**34,990.04**	**100**
Regency: Gayo Lues	1.	Blang Jerango	99.90	1,81
	2.	Blangpegayon	61.24	1,13
	3.	Pantan Cuaca	2,644.57	47,87
	4.	Pining	8.60	0,16
	5.	Kuta Panjang	11.43	0,21
	6.	Dabun Gelang	1,180.39	21,37
	7.	Blangkejeren	1,518.28	27,48
		Total	**5,524.28**	**100**
		Total DTG	**81,541.38**	**100**

Table 1 explains the existing Arabica coffee land in the Gayo Highlands, which consists of three regencies. Aceh Tengah Regency has the largest area of Arabica coffee land, covering 41,027.06 hectares spread across 14 subdistricts, while Bener Meriah Regency is the second largest, with 34,990.04 hectares across 8 subdistricts. Gayo Lues Regency has the smallest area, with only 5,524.28 hectares spread across 7 subdistricts.

3.2 Herbicide usage practices by farmers

The characteristics of herbicide usage in Arabica coffee plantations in the Gayo Highlands are presented in Table 2. Table 2 indicates that among the total observed samples, approximately 63.9% of the respondent farmers use herbicides, equating to 101 respondents out of 170. On average, farmers spray herbicides on their plantations one to two times a year, which accounts for more than 22.5% annually; furthermore, there are 18 plantations that clear their land of weeds more than three times per year. Typically, farmers remove weeds when the coffee plants begin to flower and as they approach the peak harvest period.

In other hand, 36.1% remaining farmers do not use herbicides is that they manage weeds manually using grass cutting machines. However, this method can be more than three times as expensive as using herbicides. As a result, many farmers tend to use herbicides instead. Additionally, using grass cutting machines may not provide long-term control, as weeds often regrow quickly since the method does not kill them as effectively as herbicides. Some farmers also plant vegetables between their Arabica coffee trees, which helps suppress weed growth naturally.

Table 2. Characteristics of herbicide usage in Arabica coffee plantations by respondent farmers in DTG

No.	Characteristics		Total	Percentage (%)
1	Using herbicides	Yes	156	63.9
		No	88	36.0
	Total		**244**	**100**
2	Spraying herbicides per year	1 Time	55	22.5
		2 Times	52	21.3
		> 3 Times	18	7.4
		No response	119	48.8
	Total		**244**	**100**
3	Type of herbicide		32	-
4	Herbicide dosage		10	-
5	How long do use herbicides	< 5 years	48	19.7
		5 – 10 years	47	19.3
		> 10 years	30	12.2
		No response	119	48.8
	Total		**244**	**100**
6	Reason for using herbicides	Effective, efficient, and fast	107	43.8
		Reducing labor	8	3.3
		Not capable manually	10	4.1
		No response	119	48.8
	Total		**244**	**100**
7	Acquiring herbicides	Buying from agrochemical stores	129	52.87
		Government assistance	0	0
		Cooperative assistance	0	0
		No response	115	47.13

	Total		**244**	**100**
8	Farmers' knowledge about the absorption of herbicide content by plants.	Don't Know	81	33.2
		Know	43	17.6
		Aware, controlling weeds	120	49.2
	Total		**244**	**100**
9	Farmers' knowledge of the health hazards of herbicide chemicals.	Don't Know	181	74.2
		Know	56	22.9
		Aware, but not connected to farmers	7	2.9
	Total		**244**	**100**
10	Farmers' knowledge of glyphosate residue remaining in the soil.	Don't Know	171	70.0
		Know	57	23.4
		Aware, but not concerned	16	6.6
	Total		**244**	**100**
11	The hopes of farmers	Socialized	76	31.1
		Reduced/prohibited usage/prohibited sales	30	12.3
		Farmer are assisting in controlling weeds	138	56.6
	Total		**244**	**100**
12	If the use of herbicides is prohibited, what is expected	Socialize/Control manually/Use organic herbicides	67	27.5
		Farmer are assisting in controlling weeds	94	38.5
		Differentiate coffee selling prices	83	34.0
	Total		**244**	**100**

Table 2 also indicates that herbicides are used more frequently in plantations with younger coffee plants. This is due to the fact that since the canopies of young Arabica coffee plants do not yet cover the ground between the plants, allowing weeds to grow in the gaps. Approximately 55.8% of the respondent farmers use herbicides on coffee plants that are less than 10 years old, and about 43.8% cite effectiveness, efficiency, and speed as reasons for using herbicides. If respondent farmers were to clear weeds in their plantations using a grass-cutting machine, it is estimated that they would spend three times more in terms of both money and time compared to using herbicides.

Herbicides are also easily accessible to farmers as they are freely sold in the market; more than 52.87% of respondent farmers obtain herbicides from agricultural supply kiosks. Some farmers admitted that they were unaware that the herbicides they spray to eradicate weeds can be absorbed by coffee plants and contaminate the coffee beans, while others were aware of this fact. However, because there is no price difference between organic and non-organic coffee, farmers are reluctant to spend more time and money on weed control without using herbicides.

3.3 Types and active ingredients of herbicides

Herbicides containing the active ingredients glyphosate and paraquat are both systemic and non-selective [27-29]. The use of paraquat-based herbicides has been banned, but this research indicates that herbicides containing paraquat are still being used [27]. Glyphosate-based herbicides kill weeds by translocating the active ingredient throughout the entire body or parts of the weed's tissue, starting from the leaves to the roots or vice versa [30]. It takes 1-2 days for this herbicide to kill unwanted plants (weeds) because it does not immediately kill the affected plant tissue. Instead, it disrupts the physiological processes of the tissue and is transported into the weed's plant tissue, leading to the death of its target areas such as leaves, growing points, shoots, and roots [31].

Table 3 presents the types of herbicides and the concentration of active herbicide ingredients in grams per liter (g/L). The survey results indicate that there are two types of active herbicides, namely paraquat and glyphosate, along with 22 commercials brand most used by respondent farmers. Glyphosate specifically inhibits the enzyme 5-enolpyruvyl-shikimate-3-phosphate synthase (EPSPS), which leads to the death of EPSPS cells that function as precursors for the biosynthesis of aromatic amino acids. The EPSPS enzyme converts phosphoenolpyruvate (PEP) and shikimic acid-3-phosphate (S3P) into EPSP, which serves as an important precursor for the synthesis of aromatic amino acids, folic acid, and menaquinone [32]. Furthermore, the shikimate pathway provides precursors for the secondary metabolism of plants [32], this is because enzymes in the shikimate pathway are crucial for antibiotic production. Therefore, the inhibition of EPSPS by glyphosate, which reduces aromatic acids, leads to plant death [32]. Currently, approximately 600.000 to 750.000 tons of glyphosate are used worldwide each year, and it is estimated that between 740.000 and 920.000 tons will be used by 2025 [33, 34].

Table 3. Active ingredients of herbicides in Arabica coffee plantations in Gayo Highlands (DTG)

No.	Active Ingredients	Content of Active Ingredients
1	Paraquat A	276 g/L or 276 SL
2	Paraquat B	276 g/L or 276 SL
3	Glyphosate A	166 g/L or 166 SL
4	Glyphosate B	480 g/L or 480 SL
5	Glyphosate C	490 g/L or 490 SL
6	Glyphosate D	240 g/L or 240 SL
7	Glyphosate E	240 g/L or 240 SL
8	Glyphosate F	166 g/L or 166 SL
9	Glyphosate G	525 g/L or 525 SL
10	Glyphosate H	160 g/L or 160 SL
11	Glyphosate I	486 g/L or 486 SL
12	Glyphosate J	240 g/L or 240 SL
13	Glyphosate K	530 g/L or 530 SL
14	Glyphosate L	480 g/L or 480 SL
15	Glyphosate M	240 g/L or 240 SL
16	Glyphosate N	540 g/L or 540 SL
17	Glyphosate O	480 g/L or 480 SL
18	Glyphosate P	480 g/L or 480 SL
19	Glyphosate Q	240 g/L or 240 SL
20	Glyphosate R	250 g/L or 250 SL
21	Glyphosate S	480 g/L or 480 SL
22	Glyphosate T	400 g/L or 400 SL

g/L: gram/liter; SL: Soluble liquids; A-T: Different merk of commercial herbicides.

Regulations limiting or prohibiting the use of glyphosate in agriculture have been introduced worldwide in recent years [35]. However, countries, including Indonesia, have yet to enact laws or regulations to restrict or ban glyphosate use. Limitations on glyphosate use in plantations are currently being considered in several provinces in Taiwan due to the carcinogenicity of glyphosate [36]. Herbicides applied at high doses can kill entire plant parts; however, at lower doses, herbicides may target specific plants without harming others [37]. There are concerns that herbicides with high active ingredient concentrations may be taken up by coffee plants, potentially contaminating the coffee and leading to the rejection of Gayo Arabica coffee in the global market [38].

In 2015, the International Agency for Research on Cancer (IARC) classified glyphosate as a carcinogenic substance, indicating its potential to promote cancer cell growth in humans [39]. This classification is supported by strong mechanistic evidence and a positive association with non-Hodgkin lymphoma (NHL) observed in several epidemiological studies [40]. Furthermore, the IARC also emphasized that glyphosate induces a positive trend in the incidence of renal cell carcinoma (RCC) (a malignant tumor that develops in the renal tubules) and hemangiosarcoma in male rats [41]. On the other hand, an increasing number of studies indicate that glyphosate is not an environmentally friendly herbicide [42].

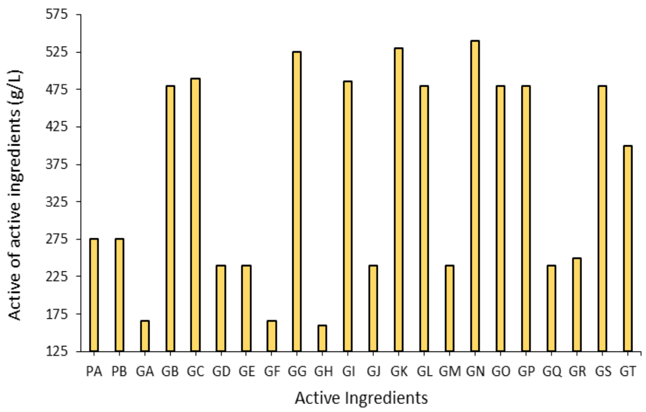

Figure 2. Active ingredients of herbicides in Arabica coffee plantations in DTG

Figure 2 shows the active ingredient of herbicides of Arabica coffee plantations from DTG, the active ingredient glyphosate is the most preferred because the herbicide is more affordable and readily available at nearby kiosks, even at village-owned businesses that sell glyphosate-based herbicide products freely. There are 10 brands of glyphosate-based herbicides used by farmers with doses of more than 400 g/Liter. Low-dose herbicide brands are no longer favored by farmers because it is likely that the weeds in Arabica coffee plantations have become resistant to lower doses [43, 44].

Glyphosates are toxic to non-photosynthetic organisms, and their toxicity levels depend on various factors, such as the method of preparing the glyphosate solution, the biological species affected by glyphosate, and environmental conditions [45]. Different commercial formulations contain varying proportions of glyphosate and other additives, resulting in different levels of efficacy and toxicity [46]. Moreover, the use of glyphosate poses potential environmental and ecological hazards [47, 48]. Consequently, the ecotoxicity of glyphosate has been increasingly studied in recent years [49, 50]. These studies have found that the use of glyphosate can disrupt soil microbial ecology and affect soil enzyme activity [51].

The use of glyphosate also has negative impacts on plant growth-promoting microorganisms, particularly including Gram-negative bacterial species such as *Burkholder* sp., *Pseudomonas* spp., and *Rhizobium* sp. [52]. Residues of glyphosate in the soil can also move through surface water, disrupting the balance of aquatic ecosystems [53]. Glyphosate also inhibits the growth of bacteria and other organisms when aromatic amino acids are not available in the environment [54], it is not surprising that herbicides have severe effects on the overall physiology of bacteria [55]. Glyphosate can reduce the susceptibility of Enterobacteria to clinically important antibiotics [56]. However, it has recently been observed that the application of glyphosate increases the prevalence of resistance genes in soil microbiota [57]. This phenomenon is attributed to antibiotic resistance genes rather than an increase in mutation rates induced by glyphosate across the genome [57].

The respondents' hopes regarding herbicide usage include raising awareness among all farmers in the Gayo Highlands about the dangers of herbicides to coffee plants, as well as for the sustainability of their land. They also seek to facilitate farmers in managing their plantations organically, particularly by assisting them in clearing their fields of weeds. Additionally, they advocate for the government and involved stakeholders to provide a price differential between organic coffee and coffee managed non-organically.

4. CONCLUSIONS

Out of 200 recorded farmer households, 101 reported using herbicides. Among the 22 commercial herbicide brands utilized by these 101 households, two active ingredients were identified: paraquat (2 brands) and glyphosate (20 brands). Given the high intensity of use (active ingredient concentration per liter and spraying frequency per year), residues of these herbicides are likely absorbed by Gayo Arabica coffee plants, posing potential risks to health and the environment. This study highlights the potential risks of glyphosate and paraquat residues in Gayo Arabica coffee plants due to high herbicide use. To address this, we recommend implementing stricter herbicide regulations, promoting organic farming practices, and exploring sustainable alternatives, such as organic fertilizers, to reduce herbicide residues and their environmental impact.

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