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ORIGINAL ARTICLE

Unregistered pesticides: Prevalence, risks, and responses in Mali

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Abstract

Improved agricultural inputs—including seeds, fertilizer, and pest control products—are necessary for raising farm productivity in Africa. Yet, in many locations, variable input quality and a proliferation of unregistered brands make product selection and calibration of optimal dosages difficult for farmers. Unregistered pesticides pose two specific quality problems: frequent underdosage and, in some cases, inclusion of banned substances. In response to widespread farmer complaints, this study estimates the prevalence of unregistered pesticide products by conducting a detailed survey of agricultural input retailers in 10 major agricultural markets across Mali. The article explores resulting risks and responses by private and public sector stakeholders through structured interviews with key informants in those same markets. The findings suggest widespread sales of low-cost, unregistered pesticides. In the 10 markets surveyed, unregistered products accounted for 26% of total pesticide volumes sold, posing risks to farmers, traders, and the environment. In response, farmer support groups and pesticide trade associations have begun to fight back through education and awareness campaigns, agro-input dealer training, farmer outreach, and in some cases, joint bulk procurement. To reinforce these initiatives, the survey results suggest two low-cost indicators for spatially targeting regulatory enforcement efforts.

KEYWORDS
pesticides, risks, unregistered, West Africa

JEL CLASSIFICATION
Q1, Q13, Q16, Q18

1 | MOTIVATION

Pesticide use has roughly tripled in West Africa over the past two decades, driven by falling prices of generic pesticides, rising costs of farm labor for hand weeding, and increases in pest pressure following the recent invasion of the Fall armyworm from the Americas (FAO, 2019; Haggblade et al., 2021).

Illegal pesticide products[1] have proliferated as well, largely because regulatory staffing and enforcement have not kept pace with the recent growth in pesticide sales across many parts of Africa (Ashour et al., 2018; Bayoumi, 2021; de Boeuf et al., 2019; Guyer, 2017; van den Berg et al., 2020; Yao, 2018). Growing concerns by African farmers, regulators and pesticide industry associations mirror international awareness of increased global trafficking in illegal pest control products (Drury, 2014; Fishel, 2018; IDC, 2021; Mace et al., 2016; OECD, 2021; Oyerle-Kano, 2022). Globally, some estimates rank illegal pesticides among the top 10 international criminal enterprises (Malkov et al., 2015). Though detailed empirical evidence remains scant in Africa, one unpublished field study of eight West African pesticide markets suggests that unregistered and counterfeit pesticides accounted for roughly one-third of pesticides sold in West Africa in 2012, albeit with wide variation across locations (Haggblade, Diarra, et al., 2019; MirPlus, 2012).

Unregistered pesticides pose two problems affecting product quality: frequent underdosage and, in some cases, inclusion of banned, toxic substances. In Mali, laboratory testing of the popular herbicide, glyphosate, found that unregistered brands contained 8%–10% less active ingredient than the registered brands, with over one-third of the unregistered products containing less than 75% of the stated level of active ingredient (Haggblade, Diarra, et al., 2019). Similar laboratory analyses of glyphosate samples from Uganda found 15% underdosage, on average, with 31% of samples containing less than 75% of the stated dosage (Ashour et al., 2018). Although the Uganda study did not directly compare dosage levels in registered and unregistered products, it did compare farmers' subjective estimates of counterfeiting and adulteration levels against measured under-dosage, finding a statistically significant but quantitatively small relationship. Farm-level productivity estimates from Mali confirm these quality differentials, finding that use of registered herbicides reduced adult male weeding labor nearly twice as much (7.9 days per hectare) as did unregistered herbicides (4.6 days per hectare) (Assima et al., 2023). The most detailed available evidence on the prevalence of banned pesticides in West Africa comes from a study in Gambia, which conducted laboratory testing of 128 pesticide products on sale in local markets. The study found that 90% of pesticide products on sale had been repackaged in unlabeled bags and bottles. Among them, 28% contained banned substances, primarily high-toxicity insecticides (Murphy et al., 2012).

Similar concerns about input quality permeate studies of fertilizer and seeds. While studies of fertilizer quality in Africa typically find nutrient content to be high for urea,[2] in contrast, they measure more frequent out-of-compliance nutrient deficiencies in NPK blends, calcium ammonium nitrate (CAN), di-ammonium phosphate (DAP), and liquid fertilizers[3] (Mbowa et al., 2015; Michelson et al., 2021; Sanabria et al., 2013, 2018a, 2018b). Bag weight shortages also prove common. As a result, farmers remain generally suspicious of fertilizer quality, even for urea, possibly because signs of visible physical deterioration of urea (such as clumping and discoloration) do not necessarily translate into chemical degradation (Michelson et al., 2021; Sanabria et al., 2013). Studies of seed markets also report large variability in quality across locations and seed types. Although many studies find low seed quality in rural markets and at farm level, causal explanations differ. While some studies identify low levels of genetic purity in hybrid and improved seed varieties (Bold et al., 2017; Gebeyehu et al., 2019; Illukor et al., 2017; Tjenstrom et al., 2017), they and others emphasize that poor seed quality – as measured by low germination rates, seedling vigor and yield – may also stem from poor seed storage and handling along the value chain (Barriga & Fiala, 2020; Gharib et al., 2021). Despite variable empirical findings about fertilizer and seed quality, this body of work consistently highlights a common concern – that widespread farmer perceptions of poor input quality, whether accurate or not, risk dampening farmer enthusiasm for adoption of productivity-enhancing inputs (Ashour et al., 2018; Barriga and Fiala, 2020; Bold et al., 2017; Gharib et al., 2021; Michelson et al., 2021; Sanabria et al., 2013).

Pesticide markets in Africa have received far less attention than fertilizer and seeds. Yet illegal pesticides pose significant risks for farmers, consumers, traders, and regulators (Bayoumi, 2021; Drury, 2014; Mace et al., 2016). For farmers, unregistered and counterfeit pesticides compromise farm productivity and safety as a result of frequent underdosage, high variability in active ingredient concentrations, inadequate labelling, product adulteration and, in some cases, inclusion of banned substances (Ashour

[1] Under most regulatory systems worldwide, illegal pesticides include unregistered products (those whose suppliers have failed to seek regulatory approval and conduct required efficacy and safety testing) as well as any pesticides sold in the market (whether registered or not) that fail to comply with prescribed quality and safety standards. Illegal pesticides, therefore, include an assortment of products that industry stakeholders refer to variously as fraudulent, fake, illicit, unregistered, counterfeit, adulterated and under-dosed. Section 2 below explores these differences in greater detail.

[2] Unlike most other studies of urea quality, Bold et al. (2017) report significant underdosing of urea in Uganda, with tested samples containing only 69% of advertised nitrogen levels, on average. This atypical result may stem from differences in testing methods (Ashour et al., 2017; Sanabria et al., 2018b; Michelson et al., 2021).

[3] Sanabria et al. (2013, 2018a, 2018b) conclude that underdosed fertilizer, as measured in multiple West and East African settings, most likely stems primarily from manufacturing deficiencies rather than malfeasance.

et al., 2018; Haggblade, Diarra, et al., 2019; Murphy et al., 2012). Traders, in turn, face significant commercial risks. Suppliers who duly comply with all regulatory testing, quality control, and labelling requirements risk losing market share to unregistered products, which incur lower costs by evading regulatory testing, fees, and compliance costs. Consumers of agricultural products face variable—through frequently unquantified—risks from pesticide residues in commonly consumed foods, including vegetables, milk products, and fish (Donkor et al., 2016; Maiga et al., 2018; Theriault et al., 2020). Environmental risks from widespread application of pesticides include possible contamination of water, soils, and animals (Jepson et al., 2014, 2020). These risks are exacerbated in locations where unregistered pesticides include banned, highly toxic substances. Unregistered pesticides pose additional, long-term risks in cases where widespread use of under-dosed or improperly applied active ingredients favor the emergence of pest resistance to major active ingredients (Chouaibou et al., 2016). Regulators charged with monitoring pesticide markets, formulation quality, and environmental impacts face numerous practical difficulties in verifying formulation dosages and residue levels, given limited budgets and a dearth of certified testing laboratories (Haggblade, Diarra, et al., 2019, 2021; van den Berg et al., 2020). Ongoing rapid growth in pesticide use magnifies these difficulties and associated risks.

This study explores these emerging risks by addressing three closely related objectives. First, it provides an empirical estimate of current levels of unregistered pesticide sales in Mali. To our knowledge, no rigorously documented, peer-reviewed study of unregistered pesticide sales currently exists in West Africa, only a smattering of expert guesstimates and a single, unpublished gray literature report (MirPlus, 2012). Second, the article tests the reliability of several proxy indicators that could potentially help to target enforcement efforts in the locations where unregistered pesticide sales are most prevalent. Finally, the article examines the policy implications of these findings, including potential remedies and emerging responses by stakeholders with a shared interest in protecting farmers, traders, consumers, and the environment from the potentially pernicious consequences of widely available unregistered pesticides.

2 | DATA AND METHODS

2.1 | Categories of illegal pesticides

To be sold legally—in the West African Sahel and, indeed, in most regulatory systems worldwide—pesticide products must comply with two regulatory requirements: (1) product registration, prior to its authorization for sale; and (2) quality compliance of subsequent market shipments with stated product standards (Table 1). The registration process involves testing of proposed products for active ingredient efficacy and toxicity, review of environmental consequences, and screening of proposed formulations for banned substances prior to authorizing a product for sale. Post-registration monitoring of product quality—including dosage levels, packaging, storage, and labelling—aims to verify compliance of products on sale with required standards, although in practice, post-registration monitoring, and enforcement often prove sporadic and geographically uneven (Haggblade et al., 2021; van den Berg et al., 2020).

Illegal pesticides include a wide range of pesticide products that fail to comply with one or both of these requirements. As a result, illegal products include an array of unregistered, under-dosed or otherwise adulterated pesticide formulations (Bayoumi, 2021; Fishel, 2018; Guyer, 2017).

2.2 | Measurement methods

The empirical work in this study focuses on measuring the market share of unregistered pesticide products currently on sale. This approach directly addresses registration status, the first of the two legal requirements for pesticide sales (Table 1). Reinforcing this choice, the few available laboratory assessments of pesticide quality in Africa all find a clear correlation between unregistered and counterfeit products, on the one hand, and low quality (including under-dosage, adulteration, or inclusion of banned substances) on the other (Murphy et al., 2012; Ashour et al., 2018; Haggblade, Diarra et al. 2019). As a result, registration status offers an easily measurable variable that may well address both dimensions of regulatory compliance.

To meet registration requirements, all pesticides sold in Mali require formal regulatory review and authorization by the Comité Sahélien des Pesticides (CSP), a regional authority set up by Mali and eight other Sahelian countries[4] that have regulated pesticides jointly since 1994 (Abiola et al., 2004; Haggblade et al., 2021). Despite this registration requirement, four different categories of pesticides currently circulate throughout Mali and the rest of the Sahelian region (Table 1). Only the first of these four categories, *authentic versions of pesticide products registered by the CSP*, can be sold legally within the borders of the nine CSP member countries (Table 1, category a).

[4] The nine CSP member countries include Burkina Faso, Cape Verde, Chad, Gambia, Guinea Bissau, Mali, Mauritania, Niger, and Senegal.

TABLE 1 Categories of illegal pesticide products

	Registered by the Comité Sahélien des Pesticides (CSP)		Not registered by the CSP	
	a. Authentic products**	b. Counterfeits***	c. Registered elsewhere	d. Not registered anywhere
1. Registered for sale in Mali and other CSP countries?*	Yes	No	No	No
2. Quality	Generally in compliance	Variable, often underdosed or adulterated	Generally in compliance	Variable, often underdosed or adulterated

*Columns b, c and d describe the three categories of illegal pesticide products on sale in Mali.

**Legally registered products supplied by the firm that registered the product.

***Imitations of registered products produced by unauthorized suppliers.

Sources: Bayoumi (2021); Fishel (2018); Guyer (2017) ; Haggblade, Diarra et al. (2019); Murphy et al. (2012); Yao (2020).

In contrast, *counterfeits* – which deliberately copy the packaging and labels of legally registered pesticides – are illegal, not only because they violate intellectual property rights of the registering firm but also because they contain unknown, often diluted or adulterated substances (Table 1, category b). Counterfeiters strive to pass off their illicit copies as originals by mimicking the packaging and labeling of well-established, registered brands as closely as possible. In some cases, counterfeiters camouflage their illegal formulations by recycling and reusing packaging material from legally registered brands (Annex Figure A1).

A second cluster of illegal pesticides includes those *registered elsewhere* (often in Ghana or Côte d'Ivoire) but which the CSP has not registered for sale in Mali and the other eight Sahelian member countries (Table 1, category c). In most cases, these include active ingredients such as paraquat, atrazine, and carbofuran, which the CSP has reviewed and specifically prohibited.

The final category of illegal pesticides includes those *not registered anywhere* (Table 1, category d). These unregistered products use packaging styles, colors, and a variety of original, inventive product names that often resemble authentic products but do not copy them exactly (Annex Figures A2 and A3). By circumventing regulatory controls, these low-cost generic products avoid the costs associated with regulatory testing and registration requirements.

Identification of pesticides not registered by the CSP (categories c and d) is relatively straightforward. It simply requires comparison of the brand labels of products on sale with the official list of pesticides registered by the CSP. Counterfeits (category b), however, are very difficult to identify with certainty, even by the major trading firms serving as manufacturers' representatives in Mali, particularly given the absence of certified pesticide testing laboratories in Mali (Haggblade, Diarra et al., 2019).

This study, therefore, focuses solely on quantifying the share of pesticides not registered by the CSP (categories c and d), which we can measure with considerable confidence. By omitting the additional, unknown level of counterfeits (category b) – which are illegal but for practical purposes unmeasurable – the research methods described below provide a *lower bound* estimate of illegal pesticide volumes sold in Mali.[5] On quality grounds, as well, measurement of unregistered pesticides (categories c and d) provides a lower bound estimate of non-compliant products. Although most quality problems occur among the counterfeits (category b) and products unregistered anywhere (category d), small levels of under-dosage do sometimes occur among pesticide products duly registered by the CSP (category a) (Haggblade, Diarra et al., 2019). As a result, measurement of unregistered pesticides (categories c and d) *understates* illegal pesticide volumes by omitting all counterfeits (in category b) as well as the handful of registered products (in category a) that sometimes fall below dosage norms. Consequently, our chosen measure of illegal pesticides—those on sale but not registered by the CSP (categories c and d)—provides an unambiguously *lower bound* estimate of illegal pesticide volumes sold in Mali.

[5] Only one, unpublished study, to our knowledge, has attempted to distinguish counterfeits from other categories of illegal pesticides. In 2012, West Africa regional regulators commissioned a study of unregistered and counterfeit pesticides covering eight countries. Their results, weighted by market size, indicate that in the early 2010's illegal pesticides accounted for roughly 34% of total pesticide sales in West Africa, 27% of them unregistered for sale by the relevant national or regional regulator plus another 7% counterfeits of legally registered brands (MirPlus, 2012; Haggblade, Diarra et al., 2019). These findings suggest that unregistered pesticides (categories c and d) account for nearly 80% of illegal pesticides on sale in the region, with counterfeits (category b) accounting for the remaining 20%. Given that the 2012 study did not conduct any laboratory testing or specify how field interviewers were expected to distinguish counterfeits from authentic brands, these results should be considered indicative rather than definitive.

2.3 | Agricultural input retailer survey

To estimate the volume of pesticides not registered by the CSP but, nonetheless, on sale in Mali, this study relies on interviews with a representative sample of agricultural input retailers across Mali's major agro-ecological zones. The markets selected cover Mali's three most important agro-ecological zones, the Guinean, Soudanien, and Sahelian zones, where over 90% of the country's crop agriculture takes place.

This survey focuses on pesticide retailers, rather than wholesalers, because unregistered products appear most visibly at the retail level where pesticide users purchase them. In June 2019, at the beginning of the 2019/20 cropping season, the research team conducted a survey of agro-input dealers in 10 agricultural markets across Mali. This timing specifically aimed to target market visits early in the cropping season, at a time when input sales and pesticide applications normally peak (Annex Table A1).

The markets selected include five large permanent markets, which open 7 days a week, as well as five smaller, weekly markets which operate only 1 day per week. This selection aimed to capture a range of markets and cropping systems representative of all major agricultural cropping zones in Mali.

In conducting the firm-level interviews, the research team collaborated with Mali's market information service, the Observatoire du Marché Agricole (OMA), enlisting OMA field staff as field interviewers for the market surveys. OMA's field staff already circulate weekly in major agricultural markets across Mali to collect agricultural input and output prices. For pesticides specifically, since OMA tracks weekly prices of a representative basket of pesticide products, the retailers are used to OMA enumerators posing questions about pesticide products they sell.

On arrival in each market, the survey team conducted a listing of all retailers selling pesticide products that day, both formal and informal. Formal retailers operate from permanent, fixed premises while the informal retailers operate from temporary sites adjacent to major markets. From this listing, the field supervisor selected 10 formal retailers and five informal retailers at random from the census listing. This resulted in up to 15 retailer interviews in each market. In total, across the 10 markets surveyed, the team interviewed 122 retail establishments, 72 formal, and 50 informal (Table 2).

A team of two enumerators then visited each of the selected retailers to administer a two-page survey instrument (see Haggblade, Keita, et al., 2019, Annex A). The survey protocol called for the retailer to first display a sample of each herbicide product on sale that day and to place the products on the display counter in order of sales volume. While one enumerator noted down the name, price, and sales percentage of each product, his/her partner photographed the label on each product. The survey team then repeated this procedure for all insecticide products and, finally, for all fungicides and other pesticide treatments. On average, the interviews lasted between 30 and 60 min each.

Following completion of the field interviews by OMA's enumerators, the research team compared all product labels with the CSP registration lists to identify the active ingredients and registration status of each product on sale. These designations, conducted by specialists on our team, required several weeks of careful review.

2.4 | Key informant interviews

During the month following the retail interviews, in July 2019, two senior researchers returned to the 10 markets to interview key pesticide sector stakeholders in order to solicit their qualitative assessment of the scope and impact of illegal pesticides in Mali as well as ensuing responses by key stakeholder groups. In total, the team interviewed 63 key informants in the 10 market towns, including 18 from the private sector, 26 from farm support organizations, and 19 from government extension and regulatory agencies (Traoré and Keita, 2019). Qualitative observations by these stakeholders have helped the research team to interpret the quantitative survey findings reported below. In addition, the key informant interviews have proven valuable in understanding the range of stakeholder responses that, in turn, frame the discussion below.

3 | RESULTS

3.1 | Overview of pesticide products sold

Herbicides account for the vast majority of pesticides used in Mali, about 75% of total volumes sold (Table 3, panel a). Insecticides make up a further 20%, while fungicides and other pesticides (nematicides, rodenticides, etc.) account for the remaining 5% of sales volume.

Herbicides likewise dominate across all categories of retailers. Among informal retailers, the dominance of herbicides jumps to 85% of total pesticide sales, while sales of insecticides, fungicides, and other pesticides remain minimal. In contrast, formal retailers sell a far larger share of more toxic products such as insecticides, fungicides, nematicides, and other pesticides than do informal retailers. Among formal retailers, insecticides account for 25% of pesticide sales, compared to only 12% for informal retailers. Similarly, with fungicides and other pesticides, formal retailers sell twice as large a share as the informals: 7% of

TABLE 2 Sampling of agricultural input retailers

	Formal retailers		Informal retailers		
Market type	**Total sellers**	**Number sampled**	**Total sellers**	**Number sampled**	**Total interviewed**
Permanent markets[a]	82	50	18	12	62
Weekly markets[b]	24	22	84	38	60
Total	106	72	102	50	122

[a]Permanent markets: Bamako main market (Quartier du Fleuve), Kati, Koutiala, Niono, Sikasso.
[b]Weekly markets: Koury, Massigui, Ouélessébougou, Yanfolila, Zégoua.
Source: Field survey.

TABLE 3 Composition of total and unregistered pesticides on sale in Mali, 2019

	Pesticide products			
	Herbicides	**Insecticides**	**Other**	**Total volume**
(a) *Composition of pesticides on sale (percent of total volumes sold)*				
Total sample	75%	20%	5%	100%
Retailer status				
Formal	68%	25%	7%	100%
Informal	85%	12%	3%	100%
(b) *Unregistered pesticides (percent of total volumes sold)*				
Total sample	24%	37%	19%	26%
Retailer status				
Formal	21%	29%	20%	23%
Informal	29%	51%	13%	31%

Source: Farm input retailer survey.

sales compared to 3% for the informal retailers (Table 3, panel a).

3.2 | Unregistered pesticide market shares

Pesticides not registered by the CSP account for 26% of total pesticide volumes sold, according to these survey results (Table 3, panel b). This observed level of unregistered pesticide volumes in Mali aligns with earlier estimates of broad averages across West Africa. An unpublished study from the early 2010s suggests that unregistered and counterfeit pesticides accounted for about 34% of total pesticide sales in West Africa, 27% unregistered products plus another 7% counterfeits (MirPlus, 2012; Haggblade, Diarra, et al., 2019). Mali's unregistered pesticide market share of 26% in 2019 corresponds closely to the 27% share estimated in 2012 for the region as a whole.

Comparing across retailer categories, informal traders sell a higher proportion of unregistered pesticides (31%) than do the formal retail shops (23%) (Table 3, panel b). This disparity is most pronounced among insecticides, where over half of the volumes sold by informal retailers are unregistered, compared to 29% for formal agro-input dealers. These findings suggest less robust regulatory scrutiny and lower regulatory compliance by informal pesticide retailers.

Of the 26% of pesticide volumes sold in Mali under brand names unregistered by the CSP, 19% are not registered anywhere. The remaining 7% have been registered by national regulators in neighboring countries (where they remain legal) but not by the CSP, making them illegal in Mali. Of these, 5% come from Ghana and 2% from Côte d'Ivoire (Table 4).

3.3 | Brand proliferation

The widespread availability of unregistered pesticide products, such as those identified in this survey, has grown hand in glove with the proliferation of registered generic pesticide brands across Africa over the past several decades (Haggblade, Minten, et al., 2017, 2021). A veritable explosion in the number of different generic pesticide brands—both registered and unregistered—has occurred in the wake of international patent expiration for many popular pesticide active ingredients and the subsequent emergence

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TABLE 4 Origin of pesticides sold in Mali but unregistered for sale there by the Comité Sahélien des Pesticides (CSP), 2019

	Pesticide category			
	Herbicides	Insecticides	Fung & other	Total pesticides
Pesticides not registered anywhere[a]	16%	32%	16%	19%
Registered elsewhere but not by the CSP[b]				
Ghana	5%	5%	0%	5%
Côte d'Ivoire	3%	0%	3%	2%
Total unregistered by the CSP	24%	37%	19%	26%

[a]Table 1, category d.
[b]Table 1, category c.
Source: retailer survey.

TABLE 5 Me-too's: Which active ingredients attract the largest number of competing brands?

Pesticide category Active ingredients	Brands inventoried	Pesticide category Active ingredients	Brands inventoried
(a) *Herbicides*		(b) *Insecticides*	
Glyphosate	59	Cypermethrin	12
Nicosulfuron	22	Lambda-cyhalothrin	10
Pendimethalin	16	Acetamiprid	10
Haloxyfop-R-methyl	14	Chlorpyrifos-ethyl	5
Prometryn	12	Emamectine benzoate	5
2,4-d	11	Carbofuran	4
Paraquat	8	Imidacloprid	4
Atrazine	7	Deltamethrin	3
Trifloxysulfuron	7	Permethrin	3
Propanil	7	Subtotal insecticides	65
Acetochlor	7		
Metolachlore	6	(c) *Fungicides and other pesticides*	
Diuron	5	Thiram	6
Others with one or two only	4	Others with one or two only	16
Subtotal herbicides	185	Subtotal	22

Note: Annex Tables A2 and A3 provide full details on active ingredient sales shares and unregistered volumes.
Source: Retailer survey.

of large-scale, low-cost generic pesticide production, and export from China and India (Huang et al., 2017).

High-volume, off-patent active ingredients attract widespread emulation and sell under multiple competing pesticide brand names. Glyphosate, the most widely sold pesticide in Mali – accounting for 38% of total pesticide volumes sold (Annex Table A2) – offers the clearest example of ongoing brand proliferation. This survey enumerated 59 different generic brands selling this single active ingredient. Other widely used herbicides containing the active ingredients nicosulfuron, pendimethalin, haloxyfop-R-methyl, prometryn, and 2,4-D and insecticides containing lambda-cyhalothrin, acetamiprid, and cypermethrin are all available under 10 or more different brand names (Table 5). No wonder farmers complain of difficulties in deciding which brand to purchase (Assima et al., 2017).

Even banned substances appear in the marketplace under multiple brand names. Although the CSP has specifically forbidden the sale of pesticide products containing the active ingredients paraquat, atrazine, acetochlor, and carbofuran, this survey found these products on sale under a range of different brand names: eight different brands of paraquat, seven different brands of atrazine, seven different brands of acetochlor, and four different brands of carbofuran.

3.4 | Price differentials

Unregistered pesticides incur lower testing and regulatory compliance costs than registered products. Likewise, limited available laboratory testing evidence suggests that unregistered and counterfeit products deliver generally

lower active ingredient dosages (Ashour et al., 2018; Haggblade, Diarra et al., 2019). Whether suppliers pass these savings along to farmers depends on farmer knowledge and their willingness to pay for higher quality. One prior study, from Uganda, finds a small price discount for low-quality glyphosate, concluding that market price indeed adjusts to lower quality but only to a very limited degree (Ashour et al., 2018).

Similarly in the current study, analysis of two of the most widely purchased pesticides—glyphosate and nicosulfuron (see Annex Table A2)—indicates a small but statistically significant price discount for unregistered products.[6] Unregistered brands of glyphosate and nicosulfuron sell, respectively, for 3.5% and 8.0% less than registered brands of comparably-dosed liquid concentrations selling in standard 1-L bottles.

3.5 | Indicators of unregistered pesticide market shares

The prevalence of unregistered pesticides varies considerably across the 10 markets studied, from lows of 10% to 12% of total pesticide volumes in the least affected markets to highs of 35% to 40% in markets where pesticide trafficking is most prevalent (Table 6). Yet resources available for monitoring and enforcement of pesticide regulations remain tightly constrained, in Mali and elsewhere in sub-Saharan Africa (Haggblade et al., 2021). In order to target scarce enforcement resources on the most acute problem areas, regulators will require tools for identifying potential danger spots quickly and inexpensively. This section explores the predictive power of seven prospective indicators—suggested during discussions with our key informants—that might potentially prove useful for spatially targeting enforcement efforts.

Three market-level characteristics our key informants considered potentially useful indicators of unregistered pesticide sales include: (1) border markets; (2) weekly markets, and (3) market size. In addition, they suggested four firm-level indicators: (4) retailer status, formal and informal; (5) number of pesticide products sold by each firm; (6) number of years each retailer has been selling pesticides; and (7) proportion of unregistered products on sale by a given firm compared to the total number of pesticide products sold (UP_i). Table 7 formally defines the resulting seven indicator variables. The subscript *i* refers to each of the 122 individual firms interviewed.

TABLE 6 Share of unregistered pesticide volumes, by market (average of all firms interviewed)

Market characteristics			Share of unregistered pesticide volumes[a]
Border?	Type	Rank order	
Yes	Weekly	1	40%
Yes	Weekly	2	35%
Yes	Weekly	3	34%
No	Permanent	4	32%
No	Weekly	5	31%
No	Permanent	6	20%
No	Permanent	7	18%
No	Permanent	8	17%
No	Permanent	9	12%
No	Weekly	10	10%

Italicized rows highlight border markets from interior markets.
Annex Table A4 reports within-market variability.
[a]Unregistered pesticide volume as a share of total pesticide volumes sold.
Source: Retailer survey.

The two equations below test the predictive power of these seven prospective indicators in estimating the share of unregistered pesticide volumes (SUV_i) in total pesticide volumes sold by each firm. The first equation examines the impact of market-level characteristics only on the share of unregistered pesticide volumes (SUV_i) in total pesticide volumes sold.

$$SUV_i = \alpha + \beta_1\ \text{Border}_i + \beta_2\ \text{Weekly}_i + \beta_3\ \text{Market sellers}_i + \varepsilon_i. \quad (1)$$

The second equation adds in firm-level characteristics as well:

$$SUV_i = \alpha + \beta_1\ \text{Border}_i + \beta_2\ \text{Weekly}_i + \beta_3\ \text{Market sellers}_i + \beta_4\ \text{Formal}_i + \beta_5\ \text{Products sold}_i + \beta_6\ \text{Years in Business}_i + UP_i + \varepsilon_i. \quad (2)$$

The results in Table 8 suggest that two of the seven suggested indicators prove effective in targeting areas with high concentrations of unregistered pesticide sales. First is the market characteristic, "border". Second is the

[6] Pesticide manufacturers make their products available in differing forms (liquid and dry granules), container sizes and concentrations, along with differing co-formulants, making apples-to-apples price comparisons difficult. From our data set, only the two most widely purchased pesticides – glyphosate and nicosulfuron – offer sufficient sample size ($n = 302$ and 141, respectively) and homogeneity in product form, packaging size and dosage levels to enable a direct comparison between the prices of registered and unregistered products. For both active ingredients, results from a one-tailed t-test of the differences in mean prices proved significant at the 99% confidence level.

TABLE 7 Prospective indicators of unregistered pesticide sales

Variables	Definition	Values		
		Mean	Min	Max
Share of unregistered pesticide volumes (SUVi)	Unregistered pesticide volume as a share of total pesticide volumes sold.	.26	0	1
Market-level indicators				
1 Border market	Dummy variable = 1 for border markets, 0 for interior markets.	.28	0	1
2 Weekly market	Dummy variable = 1 for weekly markets, 0 for permanent markets.	.49	0	1
3 Number of market sellers	Total number of pesticide sellers in each market.	22.0	11	48
Firm-level indicators (i)				
4 Formal	Dummy variable = 1 for formal retailers, 0 for informal sellers.	.59	0	1
5 Number of pesticide products sold	Total number of distinct pesticide products on sale.	13.4	1	39
6 Years in business	Number of years since retailer began selling pesticides.	10.8	1	35
7 Unregistered product occurrences (UPi)	Number of unregistered products on sale/total number of pesticide products on sale at a given firm.	.29	0	1

Source: Retailer survey.

firm-level indicator, "unregistered product occurrences (UP_i)".

In normal circumstances, instances, Equation (a) will prove most useful to Mali's pesticide regulators. Given tight resource constraints, they routinely struggle to fund the transport, fuel and overnight allowances required for conducting reconnaissance missions across multiple markets. As a result, regulators typically depend on prior knowledge from stakeholders and other external sources. These survey results indicate that border markets attract generally high levels of unregistered pesticide sales, ranging from 34% to 40% of total volumes sold, not surprising given their easy access by cross-border traders (Table 6). The results from Equation (a) confirm the importance of border markets in predicting unregistered pesticide sales. On average, firms operating in border markets sell 20% more unregistered pesticide volumes than firms selling in interior markets (Table 8 Equation a). This suggests that the simplest decision criterion regulators can use in targeting enforcement efforts is to focus first on border markets.

Interior markets, in contrast, reveal considerably greater variation in unregistered pesticide sales. Across the seven interior markets surveyed, the share of unregistered pesticides in total pesticide volumes sold ranged from 10% to 32% (Table 6). As a result, regulators require market-specific intelligence to assess the prevalence of unregistered pesticides sales volumes in any given interior market. In practice, these alarm signals most commonly come from rival traders who sell competing, legally-registered products, though also occasionally from farmer groups that flag illegal activity to local regulators.

In unusual cases, when external support permits prior reconnaissance to establish enforcement priorities, Equation (b) offers significantly greater predictive power. Its application, however, remains limited to instances in which regulators can mobilize sufficient resources to conduct firm-level interviews across multiple markets prior to launching enforcement actions. In these situations, the results in Table 8 indicate that firm-level shares of unregistered product occurrences (UP_i) provide a strong and highly significant predictor of the share of unregistered pesticides in total volumes sold (Table 8, Equation b). To illustrate, consider two retailers that both sell five different pesticide products. At one firm, four out of five pesticide products available for sale are unregistered, generating a UP_i share of .80. At the other retailer, only one out of five products is unregistered, for a UP_i share of .20. The .874 coefficient on the UP_i variable in Equation (b) predicts that the share of unregistered pesticides volumes sold will be roughly 52% higher at the first firm [(.8–.2)*.874 = .52]. These findings hold under both linear and non-linear estimating formulations as well as with and without market-level fixed effects (Table 8 and Annex Table A5).

The discussion below explores how various stakeholder groups have responded to rising levels of unregistered pesticide sales and how the empirical results reported here might improve future efforts to combat unregistered pesticide sales in Mali and elsewhere.

TABLE 8 Indicators of firm-level unregistered pesticide sales shares: Multivariate OLS regressions

	OLS regressions			
Explanatory variables	**(a) Coeff. (S.E.)**	**Sig.[b]**	**(b) Coeff. (S.E.)**	**Sig.[b]**
Market-level characteristics				
1 Border market	.198	***	.042	
	(.06)		(.03)	
2 Weekly market	−.014		−.037	
	(.05)		(.03)	
3 Number of market sellers	.003	*	.000	
	(.00)		(.00)	
Firm-level characteristics (i)				
4 Formal			−.006	
			(.02)	
5 Number of pesticide products sold			.002	
			(.00)	
6 Years in business			.000	
			(.00)	
7 Unregistered product occurrences (UPi)[a]			.874	***
			(.05)	
(α) constant term	.132	***	−.003	
	(.04)		(.03)	
Adjusted R^2	.135		.777	
With market-level fixed effects				
Adjusted R^2	.185		.779	
n=	122		122	

Notes: Dependent variable: Share of unregistered volumes (SUVi) = unregistered pesticide volume as a share of total volume sold; value ranges from .00 to 1.00.
[a]Unregistered product occurrences (UPi) = number of unregistered products on sale/total number of pesticide products on sale at a given firm.
[b]***, ** and * denote statistical significance at the 1%, 5% and 10% levels.
[c]Annex Table A5 reports results of fractional Probit estimates of these same estimating equations.
Source: Retailer survey.

4 | DISCUSSION

4.1 | Implications for on-farm pest control

In spite of the high levels of unregistered pesticides on sale, Malian farmers continue to purchase pesticides to combat crop losses arising from a wide range of pests. Unlike fertilizer, which benefits from a government price subsidy in Mali, pesticides sell at full commercial cost (Theriault et al., 2018). Rapid growth in the use of pesticides, coupled with farmers' willingness to pay full commercial price, suggests that farmers consider pesticides a cost-effective tool for controlling weeds, insects, and other agricultural pests. Indeed, Malian farmers report that weed control using herbicides now costs them roughly half as much as hand weeding (Haggblade, Smale, et al., 2017). As a result, a majority of cereal plots in the southern crop-producing zones of Mali now receive herbicide treatments, including small plots managed by women farmers. Similarly, Malian cotton and horticulture farmers apply large quantities of synthetic pesticides multiple times throughout the growing season to combat insects and fungal pests (Ajayi et al., 2002; Tefft, 2010).

Despite their current widespread use of pesticides, farmers routinely express frustration at the bewildering number of brands available (Table 5), the inconsistent quality they observe from many pesticide products and the consequent difficulty they face in selecting quality products (Assima et al., 2017; 2023). In response, organized support groups help some categories of farmers to ensure pesticide quality. Most notably, Mali's major cotton company specifies pesticide active ingredients and quality requirements and then issues bulk tenders for procurement of the cotton insecticides their 200,000-plus contract farmers require each season. Technical staff at the cotton company specify pesticide requirements during the tender process and ensure quality of the selected brands, thus protect-

ing their farmers from unregistered and often underdosed products.

Outside of the major cash crops, however, most farmers operate in unorganized value chains where they are left to their own devices in selecting from among the large number of generic pesticide products on sale for each major active ingredient (Table 5). The largest single group includes peri-urban horticulture farmers, who procure insecticides and fungicides for their small plots and apply them liberally, often alongside peri-urban water sources where they draw their irrigation water. Cereal farmers, though less heavily reliant on pesticides, face similar problems of low information and limited technical support in selecting from among the large number of active ingredients and generic pesticide brands on sale. For these farmers, brand proliferation, high levels of unregistered product sales, and variable pesticide quality pose a significant, ongoing problem.

4.2 | Implications for traders

Pesticide distributors and the international agro-chemical firms that supply them face market risks and reputational damage from the current large-scale volume of unregistered pesticides circulating in West African markets. They complain that wide variability in product quality among unregistered brands frustrates farmers and risks dampening their enthusiasm for pesticides more generally. Compounding this pressure on profits, suppliers of registered products incur significant expenses for product testing, registration, and dealer support. As they noted during our key informant interviews, these compliance fees place them at a cost disadvantage compared with the suppliers of unregistered products who avoid these regulatory and quality control costs altogether.

Not surprisingly, suppliers of registered pesticides have become strong proponents of improved regulatory enforcement (Guyer, 2017; Yao, 2020). That advocacy has translated into direct action by Mali's pesticide industry association as they engage in agro-input dealer training, public outreach, and advocacy with regulators, particularly when evidence emerges of large-scale sale of unregistered and counterfeit pesticides (Yao, 2014).

4.3 | Environmental implications

Unregistered and counterfeit pesticides complicate environmental impact measurement in several ways. Uncertainties about active ingredient content and dosage levels of the many unregistered and repackaged pesticides on sale in Mali affect sampling and testing methods. The presence of banned substances such as atrazine, carbofuran, and paraquat in many Malian markets suggests that any investigations attempting to assess pesticide impacts on human health, water, soils, and animal life will need to anticipate the full range of pesticide products actually in use, including these illegal and banned substances (see Table 5 and Annex Tables A2 and A3).

TABLE 9 Toxicity rating and unregistered product market share by pesticide category, Mali 2019

Pesticide category	Unregistered product market share	Toxicity rating*
Herbicides	24%	1.1
Insecticides	37%	2.0
Fung & other	19%	1.7
Total pesticides	26%	1.3

Notes:

WHO toxicity rating*	Assigned index
High (1a)	3
Moderate (II)	2
Slight (III)	1
Unlikely	0

Source: Retailer survey; WHO (2020), Annex Table A2.

Insecticides will merit particular attention in future environmental and human health impact assessments. As a group, the insecticides on sale in Mali have higher toxicity ratings and higher unregistered product shares than herbicides and other pesticides (Table 9). On average, Malian insecticides (weighted by sales volumes) have an aggregate toxicity rating of Moderate (II) on the World Health Organization (WHO, 2020) toxicity scale, while herbicides have a lower average toxicity rating, closer to the WHO's Slight (III) rating. Fungicides and other pesticides lie in between (Table 9).

Pest resistance also emerges as a potential concern from these survey findings, since on-farm application of high volumes of unregistered pesticides, which are more likely to be underdosed, create conditions that clearly favor the emergence of pesticide-resistant strains of weeds, insects, and other pests. If dosage concentrations vary as widely in other active ingredients as they do in glyphosate (Ashour et al., 2018; Haggblade, Diarra, et al., 2019), then risks of pest resistance become amplified. This proposition, of course, needs to be empirically verified for other popular active ingredients (such as lambda cyhalothrin and nicosulfuron) that are widely available through multiple unregistered generic brands, and this remains a research priority going forward (Table 5 and Annex Tables A2 and A3). Emerging evidence of insect resistance in rice growing zones of Côte d'Ivoire underscore these concerns, suggesting that comparable growing environments in neighboring Mali may be similarly affected (Chouaibou et al., 2016).

Interest in integrated pest management (IPM) practices has increased in response to increased pest pressure from the Fall Armyworm, locust invasions in East Africa and growing concern about initial responses centered around application of high-toxicity synthetic insecticides (Bateman et al., 2018; Day et al., 2022; Murray et al., 2019). The evidence of large-scale unregistered pesticide sales, presented above, underscores the urgency of these ongoing efforts to develop pest management practices that reduce the volumes of high-toxicity synthetic pesticides currently in use to smaller, more targeted applications as part of a broader IPM package.

4.4 | Regulatory enforcement

At the national level, a unit within Mali's Ministry of Agriculture (MoA) holds primary responsibility for monitoring pesticide markets. Due to acute budget constraints, the pesticide enforcement units within the MoA operate with limited personnel, transport resources, and storage facilities. As a result, inspections and market patrols occur only intermittently, with highly uneven geographic coverage. Logistically, the lack of transport, storage, and disposal facilities constrains the ability of national regulators to enforce pesticide registration and quality requirements. Seizure of illegal pesticides becomes difficult given the lack of safe storage and disposal facilities. An absence of certified testing laboratories in Mali makes formulation verification and quality testing impossible locally (Haggblade, Diallo, et al., 2017c).

Given their limited budgets and staffing, Mali's regulators need to target scarce enforcement resources in areas where they will achieve the greatest impact. In the absence of market-specific intelligence on illegal pesticide sales, the results from this survey suggest that pesticide regulators could most profitably focus their monitoring efforts in border markets, where sales of unregistered pesticides are generally high (Table 6). In interior markets, where the incidence of unregistered pesticide sales varies considerably, regulators will require market-specific intelligence to identify emerging "hot spots". For this purpose, the survey results suggest that simple product counts of the proportion of unregistered brands on sale by retailers in any given location offer a good indication of unregistered pesticide market shares (Table 8).

5 | CONCLUSIONS

This study has documented high levels of unregistered pesticide sales in Mali. In the 10 markets surveyed, unregistered products accounted for 26% of total pesticide volumes sold, posing problems for farmers, traders, and the environment. In response, farmer support groups and pesticide trade associations have begun to fight back through education and awareness campaigns, dealer training, farmer outreach and, in some cases, joint bulk procurement. Nonetheless, to be fully effective, these efforts by private sector stakeholders will require public sector support: in particular, improved regulatory enforcement by responsible public agencies.

Given their tight resource constraints, regulators need to target enforcement efforts on high-problem areas. In the absence of comprehensive market-specific intelligence, these survey results suggest that regulators can most profitably focus their limited personnel on border markets, where unregistered pesticides are generally most prevalent. In the infrequent instances when industry stakeholders or public agencies find ways to mobilize resources necessary for conducting market reconnaissance efforts prior to launching enforcement actions, brand counts of registered and unregistered pesticide products on sale offer an effective indicator for targeting regulatory enforcement on key problem areas.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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