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Pesticide Residue Monitoring on South African Fresh Produce Exported over a 6-Year Period

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ABSTRACT

Six years of pesticide residue data from fresh produce destined for the export market were analyzed for the period 2009 to 2014. A total of 37,838 fruit (99.27%) and vegetable (0.73%) data sets analyzed for the presence of 73 pesticides were compared. Pesticides were detected on 56.46% of samples, of which 0.78% had multiple residues. Noncompliances detected were because of the use of unregistered pesticides (0.73%), values that exceeded established maximum residue levels (MRLs) (0.32%), or the combination of values that exceeded MRLs and the use of unregistered pesticide residues (0.003%). The most commonly detected pesticides that exceeded established MRLs were imazalil (37.71%), prochloraz (28.69%), and iprodione (5.74%). The unregistered pesticide most often found on grapes and avocados was also imazalil (62.23%) and, on nectarines and avocados, diphenylamine (11.15%). Exceedances of MRL values were mostly associated with oranges (43.44%), avocados (27.87%), grapefruits (7.38%), and lemons (6.56%). Residual pesticide monitoring on fruits and vegetables is a key tool to ensure conformity with regulatory requirements and compliance with good agricultural practices and the trade requirements set by the importing country.

Key words: Fruits and vegetables; Maximum residue levels; Monitoring of pesticides; Unregistered agricultural chemical products

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To protect consumers, most countries, especially those in the developed world, have established regulatory frameworks, effective inspection bodies, and analytical laboratories with International Organization for Standardization–International Electrotechnical Commission accreditation (ISO/IEC 17025:2005) to monitor pesticide residue levels in food *(3, 13, 17, 30)*. The European Union (EU), through the European Food Safety Authority and the Standing Committee on the Food Chain and Animal Health *(34),* has been regulating pesticide residues in food since 1996 *(18, 19)*. The European Food Safety Authority annually prepares a comprehensive report about the level of pesticide residues in fruit and vegetables submitted by each member state *(24)*. The United States has also had similar pesticide monitoring programs since 1987 *(44)*.

However, globally, there is still a general lack of understanding of the significance of pesticide residues in food *(9, 40)* and their impact on the environment *(5, 10),* long-term worker safety, and public health *(4)*. In most developing countries, this information is lacking and pesticide regulation and monitoring programs are either nonexistent or are not effectively implemented so as to cover all local, exported, and imported produce *(5)*.

Since the late 1960s, the South African Department of Agriculture, currently known as the Department of Agriculture, Forestry and Fisheries (DAFF), has been doing port inspections and sampling for pesticide residues on all export consignments *(11)*. The Perishable Product Export Control Board (PPECB) is an assignee of the DAFF in South Africa, responsible for quality inspection of fresh produce destined for export, cold chain management, and sampling for pesticide residue analysis. Samples are analyzed by government laboratories *(47)*. South Africa has not, as yet, instituted a pesticide monitoring program; neither does it publish annual reports to profile pesticide residue levels on individual food commodities. This information is essential to track national residue levels in exported, imported, and local food commodities. This study provides what is to our knowledge the first national profile and analysis of pesticide residue trends for exported fresh produce over a 6-year period.

MATERIALS AND METHODS

Sampling. A total of 37,838 fruit and vegetable samples representing 61 crops were analyzed; the data were collected over a 6-year period (2009 to 2014). These export consignments were mainly destined for the EU (66.60%), with lower volumes going to the Middle East (12.29%), Asia (10.56%), Russia (3.99%), Africa (2.64%), the Far East (2.39%), North America (1.51%), and the Indian Ocean islands (0.68%). Samples were drawn randomly by trained inspectors according to the DAFF sampling standard operating procedure, which is harmonized to the European Directive 2002/63/EC sampling procedure *(16, 42)*. Samples were

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TABLE 1. *List of pesticides analyzed in fruit and vegetable export samples (2009 to 2014)*

4,4′-DDD	Fipronil
4,4′-DDE	Folpet
4,4′-DDT	Heptenofos
Azoxystrobin	Imazalil
Aziphos-methyl	Iprodione
Bifenthrin	Isazophos
Bromopropylate	Isofenfos
Cadusafos	Lindane (*gamma*-BHC)
Captab	Kresoxim-methyl
Chlordane	Malathion (mercaptothion)
Chlorothalonil	Methidathion
Chlorfenapyr	Methyl parathion
Chlorpyrifos	Nitrothal-isopropyl
Chlorpyrifos-methyl	Nuarimol
Cypermethrin	Parathion
Deltamethrin	Parathion-methyl
Diazinon	Penconazole
Dichloran	Permethrin
Dichloflaunid	Phentoate
Dicofol	Phorate
Dieldrin	Phosmet
Difenoconazole	Pirimifos-methyl
Diphenylamine	Prochloraz
Disulfoton	Procymidone
Endosulfan-alpha	Profenofos
Endosulfan-beta	Propachlor
Endosulfan sulfate	Propiconazole
Esfenvalerate	Prothiofos
Ethoprophos	Pyrazofos
Fenamiphos	Quintozene
Fenarimol	Temephos
Fenchlorvos	Terbufos
Fenhexamide	Tetradifon
Fenitrothion	Triazophos
Fenpropathrin	Trifloxystrobin
Fenthion	Vinclozolin
Fenvalerate	

drawn from different production regions and inspection points throughout the export season, according to the requested export permits. The inspection points included packing houses, cold storage facilities, and forwarding agents at air and seaport terminals. The production regions included Ceres (11.7%), Citrusdal (16.3%), Eastern Cape (19.5%), Gauteng (2.9%), Grabouw (5.5%), Natal (3.1%), Nelspruit (6.6%), Paarl (14.5%), Tzaneen (10.1%), and Worcester (9.8%).

Samples were screened for 73 different pesticides (Table 1), whose selection was based on the frequency of application and disease profiles prevalent in the country. The sample size for each product was at least 1 kg for small and medium-sized fresh fruits and vegetables and 2 kg for large-sized produce *(29)*. Samples were sealed and labeled with sample identity codes and were transported in cooler boxes for analysis to the PPECB private laboratories or DAFF national reference laboratory in Stellenbosch, depending on the geographical location of the sampling site. The PPECB private laboratories and DAFF Stellenbosch laboratory are accredited by the South African National Accreditation System (SANAS) for the International Organization for Standardization (ISO/IEC 17025:2005; SANAS Accreditation nos. T0248 and T0336, respectively). These laboratories are both managed using the same quality management system. The laboratories participate annually in the Food Analysis Performance Assessment Scheme Proficiency Testing Programme, which is managed by the Food and Environmental Research Agency in England, an internationally recognized provider of proficiency testing schemes in food chemistry, which conducts global performance benchmarking.

Extraction procedure. The extraction methods used were based on standard protocols (ASS-MTH-CR-001) *(12),* which are aligned to the EU guidance document on pesticide residue analytical methods (SANCO/3103/2000, SANCO/10476/2003, SANCO/10232/2006, SANCO/3131/2007, SANCO/10684/2009, and SANCO/12495/2011) and the analytical quality control and validation procedures for pesticide residues analysis in food and feed (SANCO/12571/2013). In short, the following were done. Fruit and vegetable samples were thoroughly shredded, homogenized, and milled into a pulp. Pulp samples (50 g) were weighed and mixed with 50 ml of water in centrifuge tubes. For citrus samples, 50 ml of saturated sodium bicarbonate solution was added instead of water (to neutralize acidity). Samples were further mixed with 50 ml of hexane-acetone (96:4) and were macerated for 20 s using a T25 digital Ultra-Turrax Macerator (IKA, Staufen, Germany). The samples were then centrifuged for 3 min at 4,000 rpm (2,862 × *g*), and the organic phase was transferred to a scintillation vial, where 2 g of sodium sulfate was added to dry the organic phase. A 2-ml aliquot of the organic phase was transferred to a 1.8-ml vial for analysis. Chemicals were obtained from Merck (Pty) Ltd (Johannesburg, South Africa).

Analysis method. The gas chromatography with dual electron capture detectors (GC-ECD/ECD) method was used for the separation and quantification of synthetic pyrethroid and organochlorine pesticides and pesticide compounds containing halogen atoms, nitro groups, and other electronegative groups. Sulfur- and phosphorus-containing compounds were determined by GC with dual flame photometric detectors (GC-FPD/FPD). The GC–halogen specific detector (GC-XSD) method was used for the separation and quantification of halogens in a dirty matrix, and the GC–mass spectrometry (GC-MS) method was used for the separation of diphenylamine in apples and pears as well as the confirmation of pesticides that had failed to meet specified regulatory requirements. Pesticide residues were confirmed when analytes were detected at acceptable levels or at above set maximum residues levels (MRLs). All results were quantified and identified against certified reference materials. Results were confirmed by a mass-specific detector (GC-MS). GC-MS confirmation was not used alone but in combination with a verification step conducted by using two columns of different polarity on the same detectors, e.g., GC-ECD/ECD with analytical column XLB and DB-17 for conventional detectors like ECD and FPD.

The Agilent Technologies 6890N and 5973N gas chromatographs (Chemitrix (Pty) Ltd, Johannesburg) were equipped with different detectors, including ECD, FPD, XSD (used mainly for quantitative analysis) and an MS detector (used for both the qualitative and quantitative analysis of pesticide residues) *(12)*. Pesticide analysis was performed on a DB-5 column (5% phenyl and 95% dimethylpolysiloxane; 30-m length by 0.32-mm inner diameter by 0.25-μm stationary-phase film thickness) and a DB-17 column (14% cyanopropylphenol and 86% dimethylpolysiloxane; 30-m length by 0.32-mm inner diameter by 0.25-μm stationary-phase film thickness). Nitrogen was used as the carrier gas for GC-ECD and GC-FPD at a flow rate of 1.5 ml/min, and helium was used for GC-XSD and GC-MS at a flow rate of 1 ml/min. The temperatures for the injector and interphase were 250 and 280°C,

TABLE 2. *Frequency of pesticide residues detected on fruit and vegetables samples over a 6-year period*

Yr	No. of samples analyzed	No. (%) of complying samples (n = 37,438; 98.95%)		No. (%) of noncompliant samples (n = 400; 1.05%)		
		Registered pesticides	No detectable pesticides	Unregistered pesticides	Exceeding MRLs	Unregistered pesticides and exceeding MRLs
2009	5,307	2,903 (54.70)	2,390 (45.03)	7 (0.13)	7 (0.13)	0 (0.00)
2010	5,805	2,983 (51.39)	2,814 (48.48)	5 (0.09)	3 (0.05)	0 (0.00)
2011	6,002	3,179 (52.97)	2,796 (46.58)	10 (0.17)	17 (0.28)	0 (0.00)
2012	7,093	3,881 (54.72)	3,178 (44.80)	10 (0.14)	24 (0.34)	0 (0.00)
2013	7,195	4,503 (62.59)	2,583 (35.90)	85 (1.18)	24 (0.33)	0 (0.00)
2014	6,436	3,516 (54.63)	2,712 (42.14)	161 (2.50)	46 (0.71)	1 (0.02)
Total	37,838	20,965 (55.41)	16,473 (43.54)	278 (0.73)	121 (0.32)	1 (0.003)

respectively. The temperature program for all GC analysis was as follows: initial temperature was 100°C for 1 min, increased at 35°C/min to 200°C, increased at 2.5°C/min to 240°C, increased at 10°C/min to 280°C, increased at 40°C/min to 340°C, and was isothermal for 6.5 min. Standard reference controls were included in all tests, and the limit of quantification was 0.01 mg/kg *(12)*.

RESULTS

A total of 37,838 samples were analyzed, and 98.95% complied with the South African set MRLs for each crop at the time of sampling. Pesticide residues were detected in 56.46% of the samples tested; of these residues, 55.41% were registered and 0.73% were unregistered for the specific crop. In total, 400 samples (1.05%) were noncompliant, and of this number, the majority (0.73%) were noncompliant due to unregistered pesticides use (Table 2). Noncompliance due to residues above set MRLs was found in 0.32% of samples, and 0.003% of samples had residues for both unregistered and registered pesticides exceeding set MRLs (Table 2).

The highest number of samples analyzed came from grapes (9,421) and oranges (8,920) (Table 3). The highest levels of pesticide residues, found on oranges (8,492 samples), were almost double those observed for grapes (4,803 samples). Similarly high levels of pesticide residues were also found on plums and prunes (1,680 samples) and lemons (1,543 samples). Mangoes were the only crop with a high percentage of samples with detected registered pesticides that exceeded set MRLs (3.13%), followed by avocados (2.38%), grapefruits (0.94%), oranges (0.59%), and lemons (0.39%); the rest of the crops had exceedance levels not greater than 0.20%. The crops with the highest number of samples positive for unregistered pesticide residues were grapes (83 samples), followed by avocados (45 samples), oranges (28 samples), pears (25 samples), apples (20 samples), and plums (14 samples).

Noncompliances found in apricots, fennel, nectarines, mangoes, pawpaws, persimmons, figs, pomegranates, pineapples, interspecific plums, prickly pears, pumpkins, raspberries, and watermelons were owing to unregistered pesticides (Table 3). Crops with residues from both unregistered pesticides and from registered, but exceeding MRL values, included apples, avocados, grapefruits, grapes, lemons, mangoes, oranges, pears, peaches, and plums. Although pesticides were detected on limes, pummelos, nectacots, kumquats, and blueberries, none had traceable levels of either unregistered or registered pesticides exceeding set MRLs.

Imazalil, the most-detected pesticide on crops for which it had not been registered (173 samples), was most frequently found in grapes (78 samples) and avocados (30 samples). After imazalil, the most-detected unregistered pesticides for specific crops were diphenylamine (31 samples) detected in nectarines and avocados (each with 13 samples) and azoxystrobin (25 samples) detected in plums (eight samples) and nectarines (seven samples). Other unregistered products recorded on occasion included tetradifon, prothiofos, methidathion, and profenofos (avocados), trifloxystrobin (pineapples), isazophos (grapes), triforine (kumquats), alpha-cypermethrin (plums and prunes), and permethrin, captan-captab (nectarines).

Over the last 2 years of the study (2013 and 2014), our results reflect a notable increase in the detection of unregistered pesticides, in particular for imazalil (in apples, avocados, grapes, and pears) and diphenylamine (in avocados and oranges). In table grapes, imazalil was not detected in the first 3 years (2009 to 2011); however, since then, a drastic increase has been noted, with 24 samples in 2013 and 53 samples in 2014. In oranges, diphenylamine was not detected in the first 4 years (2009 to 2012) but was detected in one sample in 2013 and in 12 samples in 2014. A total of 122 samples (0.32%) had pesticide residue levels exceeding set MRLs, and this noncompliance was largely attributed to imazalil (46 samples, mostly in oranges [35 samples]), prochloraz (35 samples, mainly in avocados [33 samples]), and iprodione (7 samples, mainly in plums and prunes [3 samples]).

The most frequently detected pesticide class was DMI (imidazole; 47.57%), mostly in mangoes (96.97%), avocados (96.55%), and oranges (84.03%) (Table 4). The second-most-detected pesticide class, dicarboximide, was found in 24.47% of samples, mostly in plums and prunes (98.72%), pluots (97.62%), nectarines (96.77%), and peaches (96.12%). Other pesticide classes that were dominant in crops included hydroxyanilide (SBI Class III) in grapes (44.11%), organophosphate in grapefruits (20.17%) and oranges (14.73%), and diphenylamine in apples (57.02%). Hydroxyanilide (SBI Class III), dicarboximide, and DMI (imidazole) were detected in all crops in which pesticides were common (>50 positive samples), with a few exceptions: hydroxyanilide (SBI Class III) in avocadoes,

TABLE 3. *Summary of total data analyzed per crop reflecting presence of pesticides and noncompliance*

Crop	No. of samples analyzed	Pesticide detection status, no. (%)		Noncompliance, no. (%)		
		Registered	Nondetectable	Unregistered	Exceeding MRLs	Unregistered and exceeding MRLs
Grapes	9,421	4,803 (50.98)	4,530 (48.08)	83 (0.88)	5 (0.05)	0
Oranges	8,920	8,492 (95.20)	347 (3.89)	28 (0.31)	53 (0.59)	0
Apples	4,834	945 (19.55)	3,866 (79.98)	20 (0.41)	3 (0.06)	0
Pears	3,872	339 (8.76)	3,506 (90.55)	25 (0.65)	2 (0.05)	0
Plums and prunes	3,055	1,680 (54.99)	1,355 (44.35)	14 (0.46)	6 (0.20)	0
Grapefruits	960	836 (87.08)	105 (10.94)	10 (1.04)	9 (0.94)	0
Lemons	2,046	1,543 (75.42)	493 (24.10)	2 (0.10)	8 (0.39)	0
Avocados	1,384	838 (60.55)	467 (33.74)	45 (3.25)	33 (2.38)	1 (0.07)
Nectarines	1,284	929 (72.35)	343 (26.71)	12 (0.93)	0	0
Peaches	540	297 (55.00)	237 (43.89)	5 (0.93)	1 (0.19)	0
Apricots	497	167 (33.60)	325 (65.39)	5 (1.01)	0	0
Persimmons	175	0	174 (99.43)	1 (0.57)	0	0
Blueberries	107	1 (0.93)	106 (99.07)	0	0	0
Figs	99	0	98 (98.99)	1 (0.10)	0	0
Pomegranates	92	0	85 (92.39)	7 (7.61)	0	0
Pluots	88	41 (46.59)	47 (53.41)	0	0	0
Mangoes	32	20 (62.50)	5 (15.63)	6 (18.75)	1 (3.13)	0
Pineapples	15	0	12 (80.00)	3 (20.00)	0	0
Interspecific plums	50	16 (32.00)	33 (66.00)	1 (2.00)	0	0
Prickly pears	12	2 (16.67)	8 (66.67)	2 (16.67)	0	0
Kumquats	10	3 (30.00)	7 (70.00)	0	0	0
Pumpkins	30	0	29 (96.67)	1 (3.33)	0	0
Raspberries	17	0	15 (88.24)	2 (11.76)	0	0
Nectacots	13	7 (53.85)	6 (46.15)	0	0	0
Pummelos	6	5 (83.33)	1 (16.67)	0	0	0
Watermelons	8	0	5 (62.50)	3 (37.50)	0	0
Fennel	1	0	0	1 (100)	0	0
Pawpaws	3	0	2 (66.67)	1 (33.33)	0	0
No pesticides[a]	266	0	266 (100)	0	0	0
Limes	1	1 (100)	0	0	0	0
All groups	37,838	20,965 (55.41)	16,473 (43.54)	278 (0.73)	121 (0.32)	1 (0.003)

[a] Crops with no pesticide residues detected: turnips (3), tomatoes (5), sweet potatoes (18), strawberries (2), quinces (1), proteas and cape greens (1), potatoes (45), plumcots (1), peppers (3), patty pans (12), onions (48), melons (5), marrows (1), lettuce (1), leeks (3), granadillas (4), gem squash (3), fresh dates (3), fennel (3), cucumbers (1), cherries (9), carrots (37), cabbage (2), brussels sprouts (17), broccoli (1), blackberries (1), beetroot (15), baby turnips (2), baby marrow (10), baby carrots (8), and aubergines (1), for a total of 266.

grapefruits, mangoes, lemons, pears, peaches, and pluots; dicarboximide in mangoes; and DMI (imidazole) in apricots, plums and prunes, pluots, interspecific plums, nectacots, and peaches. Other notable pesticide trends included the prominence of hydroxyanilide (SBI Class III) (44.11%) and dicarboximide (40.86%) in grapes.

DISCUSSION

This study, the first of its kind, reports on pesticide residue levels in South African fresh produce exports over a 6-year period, with an average compliance level of 98.95%. This reflects very positively on South Africa's export industry in comparison with its main trading partner, the EU, which reported 97.68% compliance for all imported produce *(21–24)*. Analyzing the trend over time, our study found compliance levels of 99.73% (5,307 samples), 99.87% (5,805 samples), 99.55% (6,002 samples), 99.52% (7,093 samples), 98.49% (7,195 samples), and 96.77% (6,436 samples) for the period 2009 to 2014. These results are comparable with similar pesticide residue monitoring programs conducted elsewhere *(21–24, 43–46)*. The EU pesticide residue program study for a similar period, 2009 to 2013, reported compliance levels of 97.4% (67,000 samples), 98.4% (77,000 samples), 98.1% (79,000 samples), 97.1% (78,390 samples), and 97.4% (80,967 samples), respectively *(43–46)*. Note that if a similar period (2009 to 2013) is compared, the EU average was 97.68% and the South African study reflected a much higher level (99.43%) of compliance.

In a similar pesticide monitoring program, the U.S. Food and Drug Administration (FDA) analyzed both domestic and imported fresh produce, with sample sizes ranging between 5,523 and 6,535 for a period between 2009 and 2012. Domestically produced food was reported to exhibit compliance levels of 98.60% (1,385 samples), 98.10% (1,449 samples), 98.40% (1,080 samples), and 97.20% (1,158 samples), respectively. Compliance levels for imported food were found to be less for the same period: 96.00% (4,196 samples), 95.10% (5,086 samples), 92.90%

TABLE 4. *Pesticide classes detected the most frequently from the 2009 to 2014 South African pesticide data analysis, as percentage of positive samples*[a]

Crop	Other chemicals (<50)	PYR	NEO	STM	DIP	ORG	HYD	DIC	DMI	Total no.
Oranges	0.65	0.18	0.08	0.01	0.11	14.73	0.03	0.22	84.03	10,374
Grapes	2.03	0	0.02	11.34	0.05	0.30	44.11	40.86	1.29	6,057
Lemons	1.53	0	0	1.27	0	16.67	0	0.69	79.84	1,890
Plums and prunes	0.23	0.29	0	0.47	0	0.23	0.06	98.72	0	1,718
Apples	5.88	0.46	0.64	0	57.02	4.68	0.09	29.48	1.74	1,089
Grapefruits	1.11	0.09	0.09	0	0.09	20.17	0	0.28	78.17	1,081
Nectarines	0	1.88	0	0.73	0	0.10	0.21	96.77	0.31	959
Avocados	0.21	0	0	0	1.36	0.94	0	0.94	96.55	957
Pears	15.98	0.41	13.69	0	25.10	2.90	0	36.72	5.19	482
Peaches	0	1.94	0	1.62	0	0.32	0	96.12	0	309
Apricots	8.15	0	0	2.72	0	0.54	0.54	88.04	0	184
Pluots	0	2.38	0	0	0	0	0	97.62	0	42
Mangoes	0	0	0	0	0	3.03	0	0	96.97	33
Interspecific plums	0	5.26	0	0	0	0	5.26	89.47	0	19
Other crops (<10)	0	0	0	0	0	35.71	4.76	28.57	30.95	42
Total	1.57	0.25	0.33	2.92	3.06	9.19	10.64	24.47	47.57	25,236

[a] Other chemicals, groups that were detected in fewer than 50 samples; PYR, pyrethroid; NEO, neonicotinoid; STM, strobilurin type: methoxyacrylate; DIP, diphenylamine; ORG, organophosphate; HYD, hydroxyanilide (SBI Class III); DIC, dicarboximide; DMI, imidazole.

(4,897 samples), and 88.90% (4,365 samples), respectively. The U.S. domestic food compliance level is similar to that reported by the EU. However, imported food is clearly at a lower level of compliance. South African exports are mainly directed to the EU (64.08%), and only 1.59% is exported to the United States *(39)*. Note that the general trend in the U.S. study over the last year (2012) reflects a similar notable decrease in compliance levels (88.90%) for imported food. This is very similar to the downward trend observed in South Africa over the last 2 years (2013, 98.49%; 2014, 96.77%).

Important to highlight, perhaps, is the scope of testing; it was much broader in the EU (685 pesticides) and U.S. (484 pesticides) studies and, also, a wider range of food products were tested. In contrast, in the South African study we reported on 73 pesticides. Both the EU and the United States tested a wider product range for more pesticides and other food-related chemicals or heavy metals, which were not assayed for in the South African study, which was focused only on fresh produce. The South African and EU MRLs are based on the EU official levels set at the time of analysis. The U.S. study was based on the residues tolerance levels set by the U.S. Environmental Protection Agency, which compare favorably to EU values *(43–46)*. In this study, we found that set MRLs exceedance levels were 0.13, 0.05, 0.28, 0.34, 0.33, and 0.71% for the 6 years from 2009 to 2014, respectively. The EU reported MRL exceedance levels of imported produce of 2.6, 1.6, 1.9, 2.9, and 2.6%, respectively (2009 to 2013). The U.S. study reported MRLs exceedance levels for domestic food of 1.4, 1.9, 1.6, and 2.8% for the 2009 to 2013 period, whereas levels for imports were 4, 4.9, 7.1, and 11.1%, respectively.

In 2011, Farag et al. *(26)* reported that MRL violations reflect a deviation from good agricultural practices; preharvest intervals (safety intervals) are often not followed and the rate of application and dosage may not be adjusted to requirements. Comparing the general trend of exceedance levels over the entire study period, South African exports are by far the most compliant in terms of MRL levels in fresh produce, compared with the EU and the United States. The notable high level of compliance of South African fresh produce exports reflects the historic fruit trade ties with Europe and the strictly regulated sanctions period during apartheid, when the industry could not afford noncompliance *(14)*. South Africa has also been exporting fresh produce to the EU for more than 100 years *(11)*, and this study is a testimony to the high quality and safety of that produce, particularly fruit, exported from the country. South African exports operate to the most stringent member state requirements so that they are sure that they meet all the legal requirements *(16)*. Furthermore, South African fruit export producers are all certified to at least one food safety standard *(35)*. After Spain, South Africa has traditionally had the most GLOBALGAP-certified fruit producers in the world *(8)*. South Africa's high level of MRL compliance is, therefore, reflective of a well-organized export industry that has been effectively regulated by the official export control inspectorate (PPECB) since 1926 *(11)*.

In our study, we found an average of 0.73% use of unregistered pesticides in export products from South Africa. In reports from the EU and the United States, unregistered pesticides were not mentioned. However, a study by Nowacka et al. *(38)* in Poland reported higher levels (2.2%) of analyzed samples with unauthorized pesticides. Arienzo et al. *(1)* in Italy reported even higher levels (4.8%), which they ascribed to incorrect agricultural practices. Jardim and Caldas *(32)* in Brazil reported a very high level (13.2%) of unregistered pesticides on tested products, which they ascribed to the minimal phytosanitary support given to certain crops and to low levels of education among growers. Over 40% of the growers are illiterate; they receive limited technical support, either do not read or do not understand the pesticide labels, and are economically vulnerable.

Over the last 2 years of this study, unregistered pesticides more than doubled (1.18 and 2.50%) in comparison with 2009 to 2012 (0.13, 0.05, 0.17, and 0.14%). The increase in the number of unregistered pesticide residues detected over the last 2 years of the monitoring period is, thus, a cause of concern. Unregistered pesticides detected on crops have been generally ascribed to spray contamination from adjacent fields, soil, or water *(6, 27)* or cross-contamination of alternate crops packed in the same packing house *(2)*. However, the South African Agricultural Registrar's Office of the Fertilizer, Farms Feeds, Agricultural Remedies and Stock Remedies Act, 1947 (Act no. 36 of 1947) officially cited the lack of available and registered pesticides for a wider scope of products *(36)*. More recently, farmers may have engaged in the risky practice of using unregistered products to ensure a quality product in the extended distribution networks *(37)*. The crop protection industry is, also, often reluctant to conduct local research and to do the necessary field trials that are required for country-specific product registration for minor crops. This is mainly due to low acreage and associated lower returns on investment *(31)*.

Imazalil was the most frequently detected pesticide (11,070 samples), followed by iprodione (6,164 samples), fenhexamide (2,674 samples), prochloraz (935 samples), and methidathion (789 samples). The popularity of these pesticides stems from their availability, low cost, and ability to control a wide range of pests on a wide scope of crops. Imazalil, also the most frequently detected pesticide exceeding set MRLs in this study, is a systemic fungicide used to control a wide range of fungi on fruits, vegetables, and ornamentals. Imazalil is also used as a postharvest treatment of citrus and other fruits to control storage decay *(7, 28)*. Erasmus et al. *(15)* reported extensive imazalil resistance within the citrus industry. This highlights the importance of correct dosages and effective management of chemicals to prevent buildup of pathogen resistance. Prochloraz is an imidazole fungicide that is widely used for control of postharvest diseases of crops such as cereals, bananas, and avocados *(41)*.

Most of the irregularities observed and reported on in this study were associated with the DMI-imidazole chemical group, which includes imazalil and prochloraz. The chemical groups associated with the fewest irregularities were acetamide, cyclodiene organochlorine, quinoline, IRAC 16, pyridinyl methylene, neonicotinoid, multi-site inorganic, DMI (piperazine), chlorophenol, 4-chlorophenyl 2,4,5-trichlorophenyl sulfone, and benzimidazole. This information provides a framework for producers, pesticide industries, growers associations, and regulators to manage pesticides more effectively because effective crop protection is a shared responsibility. In the current study, oranges (43.44%) were the crop associated with the most MRL exceedances, followed by avocados (27.87%), grapefruits (7.38%), and lemons (6.56%). Exceeding MRLs is, therefore, largely associated with fruit; but, to contextualize this statement, fruit constitutes the bulk of the exports.

In South Africa a pesticide residue monitoring program exists for fresh export products. However, no rapid alert system for food and feed has been established similar to that in the EU system, which is responsible for identifying risks in imported fruit and vegetables *(20, 25)*. Such a monitoring and alert program for food crops would provide valuable information for the country and is necessary for human health risk and exposure assessments *(7, 33)*. The present study provides an overview of pesticide residue levels over a 6-year period and provides a benchmark for local growers that can contribute to the appraisal of current agricultural practices and crop protection. However, although the possible negative impact on human health from pesticide use cannot be denied, this information could also lead to unnecessary concern among consumers, who lack appropriate information concerning the actual exposure levels. There is, thus, a need to strengthen the regulatory landscape of pesticide use in South Africa and to ensure effective communication in terms of noncompliance with all the stakeholders.

Residual pesticide monitoring of fruit and vegetables is a key tool for ensuring conformity with regulatory requirements and compliance with GAP. The majority of samples tested in South Africa over a 6-year period (98.95%) were compliant and were comparable with national and export requirements; only 0.73%, on average, contained unregistered chemicals. Further, only 0.32% exceeded set MRLs, and 0.003% of samples contained both unregistered pesticides and exceeded set national MRLs. In comparison with samples from the EU and the United States analyzed over a similar period, the South African noncompliance levels were on the same order or were better. This reflects a high level of compliance with global food safety standards and set criteria. A more effective regulatory landscape requires effective enforcement and implementation of penalty clauses for noncompliant producers. Furthermore, ongoing monitoring of pesticide residue levels will contribute to retaining compliance levels required for sustained international trade.

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