



Quantitative Estimation of Persistent Organochlorine Pesticide Residues in Milk and Some Traditional Dairy Products in the City of Tobruk, Libya

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التقدير الكمي لمتبقيات المبيدات الكلورينية العضوية الثابتة في اللبن وبعض منتجات
الالبان التقليدية في مدينة طبرق، ليبيا

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Abstract:

Persistent organochlorine pesticides (OCPs) are environmental contaminants that pose significant health risks due to their bioaccumulation and long-term persistence. This study quantitatively assessed residues of seven OCPs in fresh milk and traditional dairy products (butter and ghee) from Tobruk, Libya, and evaluated the associated health risks. Thirty samples (10 fresh milk, 10 national butter, 10 national ghee) were collected from local markets in August 2025. Residues were extracted using acetonitrile/hexane for milk and hexane for butter and ghee, followed by purification on Florisil columns. Analysis was performed using high-performance liquid chromatography with UV detection (HPLC-UV). Method validation showed recovery rates between 85% and 105%, and calibration curves exhibited correlation coefficients (R^2) greater than 0.998. Detectable residues were found in 53.3% of samples, with α -HCH being the most prevalent and concentrated contaminant, reaching 0.612 ppm in ghee. Total mean pesticide concentrations increased with fat content: 0.022 ppm in milk, 0.170 ppm in butter, and 0.791 ppm in ghee. The lipid accumulation factor (LAF) for α -HCH in ghee was 57.03, and the relative risk index (RRI) reached 35.57, indicating substantial concentration during processing. Although 90% of samples complied with Codex Alimentarius maximum residue limits (MRLs), three ghee samples exceeded permissible levels for α -HCH and p,p'-DDT. The findings confirm that traditional processing methods concentrating milk fat also concentrate lipophilic contaminants, leading to elevated residues in high-fat products. While general consumption appears relatively safe, chronic intake of contaminated ghee may pose health risks, underscoring the need for regular monitoring and source control.

Keywords: Organochlorine pesticides, pesticide residues, milk, butter, ghee, risk assessment.

الملخص:

هدفت هذه الدراسة إلى التقييم الكمي لمستويات سبعة مبيدات كلورية عضوية ثابتة وهي (α -HCH، γ -HCH، الهيتاكلور، الاندرين، الديكافول، p,p-DDT، o,p-DDT) في اللبن وبعض منتجات الالبان التقليدية في مدينة طبرق، ليبيا، وتقييم المخاطر الصحية المرتبطة بها. جُمعت 30 عينة عشوائية (10 لبن طازج، 10 زبدة وطنية، 10 سمن وطني) من الأسواق المحلية في أغسطس 2025م. تم استخلاص المتبقيات باستخدام مذيبات عضوية مناسبة وتنقيتها على أعمدة فلوريسيل، ثم

تحليلها كميًا باستخدام كروماتوغرافيا السائل عالية الأداء (HPLC) مع الكشف بالأشعة فوق البنفسجية. تراوحت نسبة استرداد الطريقة بين 85% و 105%، مما يؤكد دقتها، تراوحت قيم حدود الكشف (LOD) وحد الكشف الكمي (LQO) للمبيدات المدروسة بين 0.0002-0.0010 جزء في المليون و 0.0006-0.0030 جزء في المليون. كشفت النتائج عن وجود متبقيات قابلة للكشف في 53.3% (عينة 16) من إجمالي العينات. كان مبيد α -HCH هو الملوث الأكثر انتشاراً وتركيزاً، حيث سجل أعلى متوسط تركيز في السمن (0.612 جزء في المليون). أظهرت النتائج نمط تراكم حيوي واضح، حيث ارتفعت متوسطات التركيز الكلي للمبيدات بشكل ملحوظ مع زيادة محتوى الدهون في المنتج: 0.022 جزء في المليون في اللبن 0.170 جزء في المليون في الزبدة، و 0.791 جزء في المليون في السمن. وبناءً على ذلك، بلغ معامل التراكم الدهني (LAF) لـ α -HCH في السمن 57.03، بينما بلغ مؤشر الخطورة النسبي (RRI) للمبيدات الإجمالية 35.57 للسمن مقارنة بالحليب. معظم العينات (90%) كانت ضمن الحدود القصوى المسموح بها للمتبقيات طبقاً لـ (MRLs) المحلية والدولية (كودكس). ومع ذلك، فقد تجاوزت ثلاث عينات سمن (10% من إجمالي العينات) الحدود المسموح بها لكل من α -HCH و p,p-DDT. وبالمقارنة مع دراسات إقليمية ودولية مماثلة، كانت مستويات التلوث في منتجات ألبان طبرق أقل بشكل عام. تشير النتائج إلى أن منتجات الألبان التقليدية في المنطقة آمنة نسبياً للاستهلاك البشري، إلا أن ظاهرة التركيز الكبير للمبيدات أثناء معالجة المنتجات عالية الدهون مثل السمن تشكل خطراً صحياً محتملاً مع الاستهلاك المزمّن أو المركز، مما يؤكد ضرورة تعزيز الرقابة المستمرة على جودة هذه المنتجات ومصادر الأعلاف الحيوانية.

الكلمات المفتاحية: المبيدات الكلورية العضوية، متبقيات المبيدات، الحليب، الزبدة، السمن، تقييم المخاطر.

Introduction:

Persistent organochlorine pesticides (OCPs) represent a class of synthetic organic compounds that were widely used in agriculture and public health from the 1940s until their phased ban in many countries during the 1970s–2000s. Their unique physicochemical properties high chemical stability, resistance to biodegradation, and lipophilicity make them persistent in the environment and prone to bioaccumulation in the food chain [1, 2]. Recognized as persistent organic pollutants (POPs), OCPs are listed under the Stockholm Convention (2001) for global restriction or elimination due to their toxicity, long-range environmental transport, and potential for endocrine disruption, neurotoxicity, and carcinogenicity [2, 3].

The lipophilic nature of OCPs, characterized by high octanol–water partition coefficients (log Kow values typically ranging from 3 to 7), drives their accumulation in fatty tissues of living organisms [3]. Consequently, food products of animal origin, especially dairy products, can serve as significant carriers of these residues. Dairy cattle may ingest contaminated feed, water, or soil, leading to the transfer of OCPs into milk fat. The contamination risk is further magnified during traditional dairy processing, where physical separation and concentration of fat occur, producing products like butter and ghee with substantially higher fat content than raw milk [4, 5].

Globally, numerous studies have documented the occurrence of OCP residues in milk and dairy products, reflecting the persistence of these compounds despite regulatory bans. In Latin America, Waliszewski et al. (1997) reported mean concentrations of HCH (0.094 mg/kg) and DDT (0.159 mg/kg) in cow milk from Mexico [6]. In Brazil, Avancini et al. (2012) found that over 90% of fresh milk samples were contaminated with aldrin, DDT, and dicofol [7]. In Argentina, Benvenue et al. (1994) detected γ -HCH in 92% and heptachlor in 78% of butter samples, with many exceeding permissible limits [8]. In Africa, studies have similarly revealed OCP contamination.

Lung'aho et al. (2011) detected aldrin, dieldrin, and DDT derivatives in fresh and pasteurized milk from Kampala, Uganda [9]. Hailu et al. (2014) found that DDT derivatives were the most frequently occurring residues in cow and goat milk from Ethiopia [10]. Within the Arab region, El-Shinawy et al. (2017) reported that 30.4% of butter samples in Egypt were contaminated with heptachlor, with exceedances of European limits [11]. Hassan et al. (2016) observed endrin as the most prevalent pesticide in milk (68%) and noted three butter samples exceeding MRLs in Beni-Suef, Egypt [12]. In Jordan, Salem et al. (2009) demonstrated a contamination gradient where ghee was the most contaminated product, followed by cheese, butter, yogurt, and milk [13]. In Libya, limited data exist on OCP residues in dairy products. conducted a study in the Al-Jabal Al-Akhdar region, reporting the presence of endrin, dicofol, and p,p'-DDT in cow milk, soil, and water [14]. However, comprehensive quantitative assessments of OCP residues in traditional dairy products, particularly in pastoral regions such as Tobruk, remain scarce. Tobruk, located in eastern Libya, is an important pastoral and economic center where local dairy products are widely consumed. Livestock farming relies on various feed sources, some of which may be historically contaminated [14]. Given this context, there is a pressing need to evaluate the current status of OCP residues in milk and traditional dairy products in Tobruk and to assess the potential health risks to consumers.

This study therefore aimed to:

1. accurately quantify the levels of seven OCP compounds (α -HCH, γ -HCH, heptachlor, dicofol, endrin, p,p'-DDT, and o,p'-DDT) in fresh milk, national butter, and traditional ghee from Tobruk.
2. compare the measured concentrations with local and international maximum residue limits (MRLs) established by the Codex Alimentarius.
3. assess potential health risks using the relative risk index (RRI) and lipid accumulation factor (LAF).
4. provide a scientific basis for regulatory and preventive measures.

Materials and Methods:**Study Design and Sample Collection:**

A descriptive cross-sectional study was conducted in Tobruk, Libya, during August 2024. A stratified random sampling approach was employed to ensure representative coverage across different local markets. A total of 30 samples were collected, evenly distributed among three product categories: fresh cow milk (n = 10), national butter (n = 10), and national ghee (n = 10). All samples were obtained from local markets and small-scale producers to reflect typical consumer sources. Samples were collected in sterile, tightly sealed glass or plastic containers, immediately transported to the laboratory in insulated boxes with ice packs (maintained at 4 °C), and subsequently stored at –15 °C until analysis to prevent degradation.

Sample Preparation:

For fresh milk, each sample was thoroughly shaken to ensure homogeneity, and a 10 mL subsample was taken in amber glass vials for extraction. For butter and ghee, samples were gently melted in a water bath at 50 °C to separate the fat phase, then filtered through fat-free filter paper to remove any particulate matter. A 5 g portion of the pure separated fat was used for subsequent extraction.

Extraction and Cleanups:

The extraction protocol was optimized based on previously validated methods. For milk samples, the procedure described by Suzuki et al. was followed, utilizing an acetonitrile–hexane solvent system (1:1, v/v). In brief, 10 mL of milk was mixed with 20 mL of acetonitrile and 10 mL of hexane, and the mixture was vigorously shaken for 5 minutes. Phase separation was then achieved by centrifugation, and the upper hexane layer was carefully collected. This extraction step was repeated twice to maximize analyte recovery. The combined hexane fractions were subsequently concentrated under reduced pressure at 40 °C.

For butter and ghee samples, extraction was performed according to the method reported by Corneliusen. Approximately 5 g of the fat sample was dissolved in 25 mL of hexane with vortex mixing, followed by liquid–liquid partitioning with acetonitrile to remove co-extracted lipid interferences.

All resulting extracts underwent cleanup using 1 g Florisil solid-phase extraction columns (6 mL) as described in AOAC Official Method 970.52. The columns were preconditioned with hexane before loading the sample. Analytes were eluted with a hexane–diethyl ether mixture (85:15, v/v). The eluate was then evaporated to dryness under a gentle stream of nitrogen and reconstituted in 1 mL of acetonitrile prior to HPLC analysis.

Chromatographic Analysis:

Quantitative analysis was performed on a Perkin Elmer Series 2000 high-performance liquid chromatography (HPLC) system coupled with a UV detector. Chromatographic separation was carried out on a reversed-phase C18 column (250 mm × 4.6 mm i.d., 5 μ m particle size) maintained at 30 °C. The mobile phase consisted of an isocratic mixture of acetonitrile and water (80:20, v/v), delivered at a flow rate of 0.7 mL/min. A 10 μ L aliquot of each sample was injected, and detection was performed at 218 nm, a wavelength chosen for its suitability in detecting organochlorine pesticides (OCPs). Analyte identification was confirmed by matching retention times with those of certified reference standards (purity > 99%) purchased from Sigma-Aldrich. All samples were analyzed in triplicate to ensure reproducibility.

Method Validation and Quality Control:

The analytical method was validated using external calibration curves prepared for each pesticide over a concentration range of 0.0001–0.5 ppm. The calibration curves showed excellent linearity, with correlation coefficients (R^2) greater than 0.998 for all target compounds. Method sensitivity was evaluated by determining the limits of detection (LOD) and limits of quantification (LOQ) at signal-to-noise ratios of 3:1 and 10:1, respectively. The LOD values ranged from 0.0005 to 0.002 ppm, while the LOQ values ranged from 0.0015 to 0.006 ppm.

Method accuracy was assessed through recovery studies, in which blank milk and butter samples were spiked with known amounts of the target pesticides at two concentration levels (0.01 and 0.1 ppm). Recoveries ranged between 85% and 105%, falling well within the generally accepted range of 70–120% for pesticide residue analysis in food matrices. To monitor for potential contamination, procedural

blanks (solvent only) and matrix blanks were included in every analytical batch. All determinations were performed in triplicate, and results are expressed as mean values.

Statistical Analysis:

Data were statistically analyzed using SPSS software (version 22.0, IBM Corp., Armonk, NY, USA). Descriptive statistics, including means, standard deviations, and coefficients of variation (CV%), were calculated for each pesticide across the different dairy product categories. Differences in mean concentrations among milk, butter, and ghee samples were evaluated using one-way analysis of variance (ANOVA). When significant differences were detected, Tukey's post-hoc test was applied for multiple comparisons. A p-value of less than 0.05 was considered statistically significant.

Risk Assessment Indicators:

To evaluate the relative exposure risk and accumulation tendency of OCPs in fatty dairy products, **two simple indices were calculated:**

- **Relative Risk Index (RRI):** the ratio of the sum of mean pesticide concentrations in fatty products (butter and ghee) to that in milk. An RRI value greater than 1 indicates a higher potential risk associated with the consumption of high-fat dairy products.
- **Lipid Accumulation Factor (LAF):** the ratio of the concentration of a given pesticide in a fatty product to its concentration in fresh milk. This factor reflects the extent of pesticide accumulation during processing.

These indicators offer a straightforward quantitative approach to understanding how fat content and processing influence pesticide levels in dairy products.

Results:

Occurrence and Distribution of OCP Residues:

Of the 30 samples analyzed, 46.7% (n = 14) showed no detectable residues of the target pesticides, while 53.3% (n = 16) contained at least one compound. Out of the seven pesticides monitored, five were detected: α -HCH, dicofol, endrin, p,p'-DDT, and o,p'-DDT. In contrast, γ -HCH and heptachlor were not found in any sample. The overall mean concentration of total pesticide residues across all samples was 0.064 ppm.

As shown in Figure X and Table 1, both the frequency of occurrence and the residue concentrations varied considerably among product types. In fresh milk, four pesticides were detected. Endrin was the most frequently found compound (30%), with a mean concentration of 0.00016 ppm, followed by α -HCH and dicofol. The total mean pesticide burden in milk was low (0.02225 ppm) and remained well below established maximum residue limits.

In butter samples, five pesticides were identified. Dicofol showed the highest detection frequency (40%) and the highest mean concentration (0.05410 ppm), followed by p,p'-DDT (30%) and endrin (20%). The cumulative mean concentration of all detected pesticides in butter reached 0.17042 ppm.

Ghee samples exhibited markedly higher contamination levels. α -HCH was the most prevalent compound (30% detection frequency) and recorded the highest mean concentration (0.6119 ppm). The total mean pesticide concentration in ghee was 0.79144 ppm. Notably, three ghee samples exceeded the maximum residue limits (MRLs) for α -HCH and p,p'-DDT, raising potential concerns regarding the safety of these products for regular consumption.

Table (1): Distribution of OCP Residues in the Milk and Dairy Product Samples (n=30)

National Ghee (n=10)	National Butter (n=10)	Milk Samples (n=10)	Parameter	Pesticide Type
%30.0	%20.0	%20.0	Occurrence Rate	-HCHα
0.6119	0.05169	0.01073	Mean Conc. (ppm)	
%20.0	%40.0	%20.0	Occurrence Rate	Dicofol
0.07306	0.05410	0.00761	Mean Conc. (ppm)	
%20.0	%20.0	%30.0	Occurrence Rate	Endrin
0.04158	0.02400	0.00016	Mean Conc. (ppm)	
%10.0	%30.0	%10.0	Occurrence Rate	p,p'-DDT
0.06491	0.02381	0.00250	Mean Conc. (ppm)	
%0.0	%10.0	%0.0	Occurrence Rate	o,p'-DDT
ND	0.01582	ND	Mean Conc. (ppm)	
0.79144	0.17042	0.02225	Total Mean Concentrations (ppm)	

(ND: Not Detected)

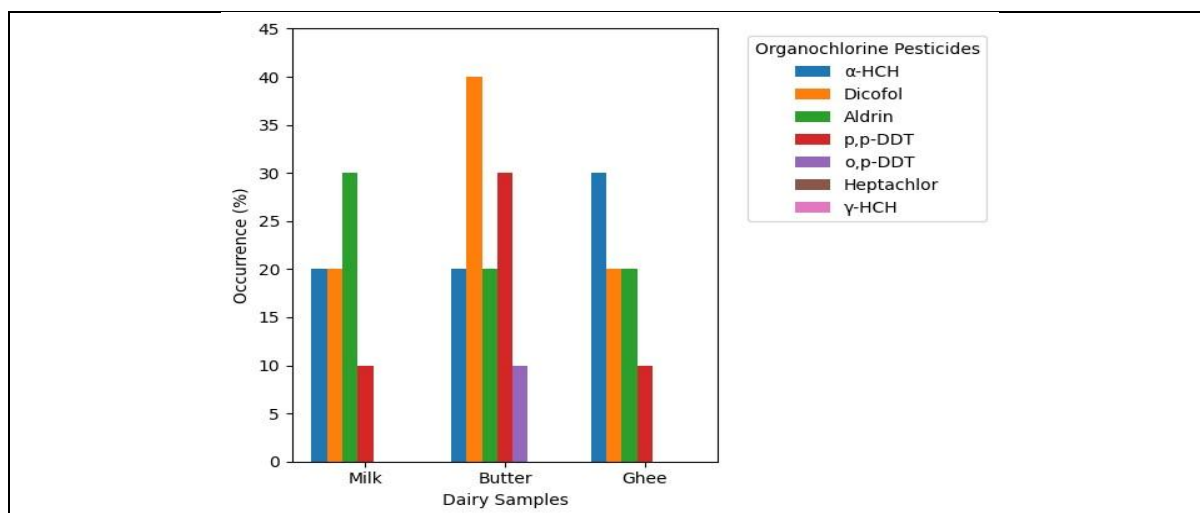


Figure (1): Distribution of OCP Residues in the Studied Milk and Dairy Product Samples (n=30)

Variability and Descriptive Statistics:

The coefficient of variation (CV%) for detected pesticides ranged from 33.1% to 42.7% (Table 2), indicating substantial variability in contamination levels among individual samples. This heterogeneity suggests diverse sources of milk and differences in processing practices.

Table (2): Descriptive Statistics for OCPs detected in all Samples (n=30)

Overall Mean (ppm)	Range (ppm)	CV (%)	Frequency (n)	Occurrence Rate(%)	Pesticide
0.227	0,612-0015	42.7	7	23.3	α-HCH
0.044	0,121-0021	38.2	8	26.6	Dicofol
0,022	0,042-0,00016	35.9	5	16.6	Endrin
0.030	0,065-0,00025	33.1	4	13.3	p,p-DDT

MRL Compliance and Risk Indicators:

Of the 30 samples analyzed, 27 (90%) complied with the maximum residue limits (MRLs) set by the Codex Alimentarius for organochlorine pesticides. The three samples that exceeded these limits were all ghee, accounting for 30% of the ghee samples examined and 10% of the total sample set. These exceedances involved α-HCH and p,p'-DDT.

The Relative Risk Index (RRI) revealed a substantially higher exposure potential in the fatty products relative to milk, with values of 7.66 for butter and 35.57 for ghee. Likewise, the Lipid Accumulation Factor (LAF) for α-HCH was calculated as 4.91 in butter and rose dramatically to 57.03 in ghee. These results underscore the significant concentration of pesticide residues that occurs during the traditional processing of ghee, clearly illustrating how both fat content and processing methods contribute to the accumulation of organochlorine pesticides in dairy products.

Discussion:

Concentration Patterns and Processing Effects:

The findings reveal a clear progressive increase in total organochlorine pesticide (OCP) residues from fresh milk to butter and finally to ghee, showing a strong positive association with fat content. This pattern aligns with the well-established lipophilic character of OCPs, which causes them to preferentially partition into the fat phase during dairy processing [4, 5].

Traditional ghee production involves extended heating along with the removal of water and non-fat solids, thereby concentrating the fat content from roughly 3–5% in milk to over 99% in the final product. As a result, lipophilic contaminants such as organochlorine pesticides that are initially present in the milk fat become markedly concentrated during processing.

The Lipid Accumulation Factor (LAF) of 57.03 observed for α-HCH in ghee indicates that the concentration of this pesticide is more than 57 times higher in ghee than in the original milk. This substantial enrichment highlights the need to monitor not only raw milk but also processed high-fat dairy products, which may present considerably greater exposure risks on a per-unit-weight basis.

Sources and Historical Persistence:

The detection of α -HCH, DDT derivatives, and endrin, compounds banned in Libya for many decades, highlights their remarkable environmental persistence. Likely sources include legacy agricultural applications, long-range atmospheric transport, and contamination of animal feed. Of particular note is the predominance of α -HCH among the detected residues. This isomer is known to be significantly more stable and resistant to microbial degradation than the other HCH isomers [3].

The elevated levels of α -HCH observed in ghee suggest that dairy cattle in the region were likely exposed through contaminated feed, either from crops grown on soils still bearing residual contamination or from imported feed originating in countries where HCH usage has historically been more widespread. This interpretation is supported by a recent study by Smith and Raikwar (2025), which reported that legacy organochlorine pesticides, including those no longer permitted under MRL regulations, continue to be detected in animal feed worldwide [3].

Variability and Implications for Monitoring:

The relatively high coefficients of variation (33–43%) reflect substantial variability in contamination levels across the samples. This heterogeneity can be attributed to several factors, including (i) differences in milk sources (small-scale farms versus larger commercial producers), (ii) variations in feed composition and grazing practices, (iii) historical differences in pesticide application on pastures, and (iv) non-standardized traditional methods used in household processing of butter and ghee. Such variability suggests that results based on a limited number of samples may not provide a reliable picture of the overall contamination status. Therefore, regular and systematic monitoring programs involving larger sample sizes are essential to better capture the true distribution of residues and to identify potential contamination hotspots.

Comparison with National and International Studies:

When compared with previous reports (Table 3), the levels of organochlorine pesticide residues found in Tobruk dairy products are generally lower than those documented in many countries with a history of intensive agriculture. For example, Avancini et al. (2012) reported a 90% contamination rate with endrin and DDT in Brazilian samples, with concentrations notably higher than those observed in the present study [7]; Benvenue et al. (1994) reported very high detection frequencies of γ -HCH and heptachlor in butter samples from Argentina [8]; Similarly, Egyptian studies have documented the widespread occurrence of endrin and heptachlor in dairy products, with several samples exceeding the established maximum residue limits (MRLs) [11, 12]. The comparatively lower residue levels observed in Tobruk likely reflect the region's predominantly pastoral and less industrialized agricultural system, which has experienced relatively limited historical use of organochlorine pesticides. This finding aligns with an earlier study conducted by Al-Awami and Elgoul (2016) in the Al-Jabal Al-Akhdar region, which similarly reported moderate levels of contamination in dairy products [14]. Nevertheless, the detection of OCP residues, particularly the exceedances observed in ghee, demonstrates that the region is not entirely free from the long-lasting global legacy of organochlorine pesticide contamination.

Table 4: Comparison with Previous Studies on OCPs in Dairy Products

Key Findings (Prominent Pesticides, Rates, Concentrations)	Sample Type	Study (Country, Year).
(90%) within MRLs. α -HCH mean 0.612 ppm. in ghee: 3ghee samples exceeded MRLs	cow milk, butter, l ghee	This Study Libya, 2025
Most Endrin, 11.6 mg/kg. Most samples exceeded MRLs	cow and goat milk	Ethiopia Hailu, 2014 [10]
90% samples contaminated. - Endrin: 44%. - DDT: 36%	fresh cow milk	Avancini, Brazil 2012 [10]
Endrin 68% in milk. - 3 butter samples exceeded limits	cow milk and butter	Waliszewski, - Mexico, 1997 [6]
Heptachlor: 30.4% in milk. - 3 butter samples exceeded MRLs	milk, cream, butter	Egypt Hassan, 2016 [12]
Contamination order: ghee > cheese > butter > milk; HCH and DDE exceeded limits	milk, butter, cheese, ghee	Salem, 2009- Jordan [13]
γ -HCH 92%. - Heptachlor 78%. - Exceeded standards	samples: butter	Benvenue, 1994 Argentina [8]

Health Risk Implications:

Although most samples complied with the established maximum residue limits (MRLs), the presence of organochlorine pesticide (OCP) residues in traditional dairy products, and particularly their marked concentration in ghee, deserves careful consideration. Chronic dietary exposure to OCPs, even at

concentrations below regulatory limits, has been linked to endocrine disruption, neurodevelopmental disorders, and elevated cancer risk [17, 18].

The Relative Risk Index (RRI) of 35.57 for ghee indicates that consumption of this product may result in approximately 35 times higher pesticide exposure compared with an equivalent amount of milk. In practical terms, individuals who regularly consume large quantities of ghee could face a substantially higher cumulative intake of these persistent compounds. Vulnerable groups, including children, pregnant women, and nursing mothers, may be at particular risk due to the potential for transplacental and lactational transfer of OCPs [18]. While occasional consumption is unlikely to pose significant risk to the general population, long-term or high-intake scenarios should be taken into account in future risk management strategies.

Limitations and Future Research:

The present study has several limitations. Although the sample size was sufficient for a preliminary investigation, it remains relatively small and covers only a single season. Residue levels may vary with seasonal changes in feed sources and environmental conditions. Furthermore, the study did not include analysis of soil, water, or animal feed, which would have helped trace the origins of contamination more directly. Future research should therefore expand the geographic scope, incorporate multi-seasonal sampling, and include source matrices such as soil, water, and feed. In addition, a comprehensive quantitative health risk assessment based on local consumption patterns and acceptable daily intake (ADI) values would provide a more robust basis for risk communication and policy development.

Summary:

- OCP residues were detected in 53.3% of the analyzed samples, with α -HCH being the most frequently occurring and abundant contaminant.
- Total pesticide concentrations increased markedly with fat content, following the order: ghee > butter > milk.
- Ninety percent of samples complied with Codex Alimentarius MRLs; however, three ghee samples exceeded the limits for α -HCH and p,p'-DDT.
- The Relative Risk Index (RRI) for ghee reached 35.57, while the Lipid Accumulation Factor (LAF) for α -HCH was 57.03, clearly demonstrating the significant concentration effect during traditional ghee processing.
- Overall, the dairy products examined appear relatively safe for general consumption, although chronic intake of high-fat products such as ghee may warrant attention from a health risk perspective.

Recommendations:

- Routine monitoring of OCP residues in high-fat dairy products (especially ghee and butter) should be integrated into national food safety surveillance programs.
- Inspection and control measures for animal feed should be strengthened, with particular attention to imported feed that may carry legacy OCP residues.
- Awareness campaigns targeting farmers and traditional processors are recommended to highlight potential sources of contamination and promote good agricultural and processing practices.
- Further research should be extended to other regions of Libya, include seasonal sampling, and incorporate analysis of soil, water, and feed to better identify contamination pathways.
- A quantitative health risk assessment utilizing local consumption data and acceptable daily intake (ADI) values should be conducted to refine risk estimates and support evidence-based decision-making.

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