Comprehensive Profiling of Chemical Contaminants in Farmed Beluga Caviar: Multi-Residue Analysis of Pesticides, Synthetic Dyes, Heavy Metals, and Antibiotics

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Abstract:

Introduction: Caviar, a luxury food product derived from sturgeon, may contain pesticides, dyes, antibiotics, and heavy metal residues, making a comprehensive risk assessment essential for consumer safety.

Objective: This study specifically investigated the concentrations of diverse contaminant residues in aquaculture-produced caviar. Multiple analytical approaches can be employed to identify and measure contaminant residues in caviar.

Material and Methods: In this study, liquid chromatography-tandem mass spectrometry, gas chromatography-tandem mass spectrometry, and inductively coupled plasma mass spectrometry were employed to determine 55 target residues, including three heavy metals, nineteen organochlorine pesticides, seven organophosphate pesticides, twenty-two antibiotics, and four dye residues in Beluga sturgeon (*Huso huso*) caviar samples. The samples were collected from major Iranian aquaculture facilities (16 sturgeon farms) located in the provinces of Gilan, Mazandaran, Golestan, Qom, and Fars during the 2024-2025 production cycle.

Results: The study revealed that heavy metal levels did not exceed 10 µg/kg, dye residues were beneath 0.2 µg/kg, and the pesticide residues were under 5 µg/kg. Additionally, the antibiotic residues present in the samples were below the detection threshold and in compliance with European Commission food regulations.

Conclusion: The results of this survey can be attributed to the effectiveness of modern, controlled farming practices, such as monitoring water quality, optimized feeding schedules, and notice to veterinary drug withdrawal periods. Furthermore, it can be concluded that the levels of pesticide, synthetic dye, heavy metals, and antibiotic residues in Iranian cultivated caviar were beneath the method's limit of detection (LOD) and do not pose health concerns for consumers.

Keywords: Anti-Bacterial Agents; Coloring Agents; Metals, Heavy; Pesticides

1. Introduction

As people's lifestyles evolve and societies become more industrialized, public concern about potential and actual chemical and microbial hazards in various food products has increased. In this context, the rise in the use of agricultural chemicals and pesticides, climate change, and the adoption of new technologies have led to excessive levels of these contaminants entering consumers' diets, exceeding safe limits, and ultimately increasing public concern, prompting regulatory actions by veterinary and food authorities in various countries [1].

Caviar, a raw animal product, is derived from the sturgeon fish. The value of sturgeon fish is not only for their meat but mainly for the caviar obtained from them, which has exceptionally high economic value. The production volume of farmed caviar in Iran is 21 tons [2-4].

Twenty-seven sturgeon species are found throughout the Northern Hemisphere, with six of the most important global species inhabiting the Caspian Sea, which alone contains 93% of the world's sturgeon populations. These include *Acipenser stellatus*, *Acipenser ruthenus*, *Acipenser persicus*, *Acipenser gueldenstaedtii*, *Huso huso*, and *Acipenser nudiventris*. These species are now listed as critically endangered [5-7].

Monitoring and analyzing residual contaminants, including hormones, antibiotics, anthelmintics, dyes, pesticides, and heavy metals, in farmed caviar has become critically important due to the potential use of pharmaceuticals and chemicals in aquaculture practices, as well as possible environmental contaminant exposure. With the recent increase in farmed caviar production, ensuring the safety and quality of these products through comprehensive evaluation and control of residues has become a top priority for both regulatory compliance and consumer safety [8-10].

According to EU guidelines, monitoring heavy metals and various analytes (such as antibiotics, anthelmintics, organochlorine/organophosphate/pyrethroid pesticides, hormones, dyes, and heavy metals) in farmed fish becomes especially important.

A study conducted from March to April 2011 determined the accumulation of Zinc (Zn), lead (Pb) and cadmium (Cd), in Persian sturgeon caviar sourced from the southern Caspian Sea coast, the mean levels of Zn, Pb, and Cd in the caviar were 44.73, 2.11, and 0.01 µg/g, respectively [11].

In a study conducted on Persian sturgeon caviar collected from a sampling location in the Southern Caspian Sea, the average concentrations (mg kg^{-1}) of As were 0.01, Cd 0.05, Cu 1.42, Co 0.01, Pb 0.01, and Sn 0.28various heavy metals and metalloids were determined as follows: [12].

In a comprehensive environmental contaminant assessment, concentrations of both organic contaminants (such as polybrominated diphenyl ethers (PBDEs), dichlorodiphenyltrichloroethane (DDT), polychlorinated biphenyls (PCBs), and hexachlorocyclohexanes (HCHs)) and inorganic pollutants (a suite of 23 metals) were determined in caviar obtained from *Acipenser stellatus, Acipenser gueldenstaedtii*, and *Huso huso* sourced from Iran, Bulgaria, Azerbaijan, and Russia. Analytical results showed average contaminant concentrations of 15.47 ± 25.8 ng/g wwt for PCBs, 797 ± 139 ng/g wwt for DDT, and 9607 ± 486 ng/g wwt for arsenic, with PBDEs being detected in all samples [8].

According to those mentioned above, this study was performed to assess 55 target residues (pesticides, antibiotics, heavy metals, and dyes) in sturgeon caviar samples collected from major Iranian aquaculture facilities during the 2024-2025 production cycle.

2. Materials and Methods:

The research method employed a quantitative approach, based on data collected from samples of farmed caviar produced in Iran and the results of laboratory tests performed on these samples. Beluga caviar samples were obtained from *Huso huso* fish (1.6–2 m in length, 35–70 kg in weight, and 10–14 years of age) that were cultured in 16 sturgeon farm in the Giulan, Mazandaran, Golestan, Qom, and Fars provinces of Iran (Table 1).

Table 1. Geographical distribution of the sampled farms.

Province	Number of caviar producing farms	Number of sampled farms
Gilan	15	**9**
Mazandaran	5	**3**
Golestan	2	**1**
Qom	3	**1**
Fars	2	**1**

2.1. Sample preparation and heavy metal analysis

Heavy metal levels in the samples were determined following standard protocols BS EN 13806:2002 and BS EN 1550:2007 for sample preparation and measurement. Approximately 50 g of the sample underwent homogenization to ensure uniformity, after which a 0.3 g aliquot was transferred into the microwave digestion vessels (Anton Paar GmbH, Germany). Subsequently, 2 mL of 30% H_2O_2 and 3 mL of 65% HNO_3were added, followed by a 20-minute pre-digestion period to allow for reaction stabilization. The vials were then placed in a microwave and subjected to an appropriate digestion cycle. Following digestion, the vials were cooled at ambient temperature for 20 minutes, after which the resulting digest was quantitatively transferred into 30 mL volumetric flasks and made up to volume with double-distilled water. For analysis, the solutions were transferred to special vials for atomic absorption spectroscopy (AAS). Lead and cadmium concentrations were measured using a graphite furnace atomic absorption spectrometer (Agilent, USA). Mercury (Hg) was analyzed with a mercury analyzer employing the cold vapor technique. The sample was converted into mercury vapor and directed into a gas cell, where absorption was measured at the specific wavelength of a mercury lamp [13].

2.2. Sample preparation and analysis of organochlorine pesticides

To quantify organochlorine pesticides, including β-HCH, γ-HCH, hexachlorobenzene (HCB), α-hexachlorocyclohexane (HCH), aldrin, chlordane (cis- and trans-), endrin, heptachlor, methoxychlor, heptachlor epoxide, DDT isomers, pendimethalin, dieldrin, endosulfan (α-, β-, and sulfate), dicofol, and chlorothalonil, approximately 1 g of caviar was homogenized with anhydrous sodium sulfate. The resulting mixture was then transferred to a pre-washed extraction thimble that had been rinsed with hexane. Prior to the extraction step, the following internal standards were added: PCBs 46 and 143 (10 ng each), ε-HCH (7.5 ng), brominated biphenyl 103 (2 ng), and brominated biphenyl 15 (0.5 ng). After that, the sample was extracted for two h at hot temperature with 75 mL of a hexane/acetone blend in a 3:1 volume ratio. After concentrating the extract to roughly 5 mL, an aliquot of about one-sixth of the volume was taken for fat content analysis, performed by solvent evaporating at 105°C for 1 h. The remaining extract was subsequently loaded onto a cartridge packed with 8 g of silica gel that had been pre-treated with 44% concentrated sulfuric acid. The target compounds, including polybrominated diphenyl ethers, polychlorinated

biphenyls, and organochlorine pesticides, were completely eluted with 15 mL of *n*-hexane followed by 10 mL of dichloromethane. The collected eluate was then concentrated using rotary evaporation and further reduced to near dryness (Agilent, USA) under a gentle nitrogen stream. The residue was reconstituted in 80% iso-octane, after which the solution was subjected to analysis for persistent organohalogenated pollutants [14, 15].

2.3. Sample preparation and measurement of organophosphate pesticides

The analytical method for six organophosphate pesticides (trichlorfon, malathion, chlorpyrifos, phoxim, profenofos, diazinon, and fenitrothion) began with homogenization; To a 50 mL polypropylene centrifuge tube, 1 g of the homogenized sample was added, followed by the addition of internal standards and target analytes for recovery evaluation. After equilibrating for 15 min, the sample was supplemented with 10 mL of acetonitrile and shaken vigorously for 30 s. The extract was then transferred to another 50 mL centrifuge tube pre-loaded with 4 g of anhydrous $MgSO_4$ and 1 g of NaCl. This was followed by vigorous shaking for 1 minute and centrifugation at 3,250 rpm for 2 min. Subsequently, a 1 mL aliquot of the supernatant was added to a 2 mL centrifuge tube pre-loaded with anhydrous $MgSO_4$ (150 mg), C18 (50 mg), PSA (50 mg), and ZrO_2 (50 mg). The mixture was vigorously shaken (30 s) and centrifuged (3,250 rpm for 2 min), after which 0.5 mL of the purified extract was dispensed into an autosampler vial for GC-MS/MS analysis [15, 16].

2.4. Sample Preparation and Analysis of Dye Residues

Detection of dye residues (Leucomalachite green, Crystal violet, Leuco crystal violet and Malachite green) was performed as follows: Two grams of homogenized sample were weighed, followed by the integration of 40 µL of internal standard mix (100 ng/mL). Subsequently, 500 µL of hydroxylamine solution (9.5 g/L) was introduced, and the mixture was vortexed for 2 minutes before being incubated in the dark for 10 min. Following that, 8 mL of acetonitrile and 0.1 g of anhydrous $MgSO_4$ were introduced. Next, vortexing of the mixture was carried out for 2 min, and then it was shaken at 100 rpm for 10 minutes. Following centrifugation for 5 minutes, the supernatant (4 mL) was gently pipetted into a clean tube and dried completely at 50°C using a gentle flow of nitrogen.

The residue after drying was dissolved in 1000 µL of a solution containing acetonitrile and 1 g/L ascorbic acid (1:100, v/v), then vortexed for 2 min, and finally filtered via a 0.22 µm PVDF syringe filter. Quality control measures included spiking selected samples at levels of 0.1, 0.25, 0.5, and 1 ng/g. The spiked samples were equilibrated for 1 h prior to extraction, which was performed using the method detailed above. Ultimately, a calibration curve was created using the spiked samples, enabling the determination of analyte concentrations by comparing peak areas with the calibration equation [17].

2.5. Sample preparation and analysis of antibiotic residues

First, 3 g of the sample was introduced into a 50 mL screw cap tube. The procedure continued with the addition of 15 mL of methanol (70%) and 200 µL of EDTA (0.1 M). The homogenization of the mixture was performed for 1 min using a high-efficiency disperser, and subsequently centrifugation at 3800 × g for 5 min. Once centrifugation was complete, the supernatant (500 µL) was carefully transferred to polypropylene tubes, admixed with purified water (2 mL), and passed through 0.45 µm filters before analysis. The prepared samples were analyzed using an LC-MS/MS, which was fitted with a Turbo V ion source and an electrospray ionization probe. For chromatographic separation, a C18 Synergi column was used, while data collection and process were conducted with Analyst 1.6.2 software. The mobile phase comprised two solvents: phase A, containing 0.2% formic acid and 0.1 mM oxalic acid in water, and phase B, consisting of 0.2% formic acid and 0.1 mM oxalic acid in acetonitrile.

The optimized gradient program started with an increase in mobile phase B from 0% to 75% within 1 min, followed by a hold at 75% for 1.6 min. Subsequently, the composition was returned to 0% B over 4.6 min, giving a total run time of 7.2 min per injection. For mass spectrometric detection, the instrument operated in negative ionization mode for AMFs and in positive ionization mode for antibiotic residues, following the method described by Yipel et al. (2017) [18].

3. Results

According to the results, the tested caviar poses no significant health risk from heavy metal contamination, since the levels of lead, mercury, and cadmium were all beneath the quantifiable limit of 10 µg/kg. This finding underscores the high quality and safety of this luxury product (Table 2).

Table 2- Concentrations of heavy metals in farmed beluga caviar determined by ICP-MS

Heavy metal	Detection limit (µg/Kg)	Result (µg/Kg)
Lead	10	**<10**
Mercury	10	**<10**
Cadmium	10	**<10**

Analytical results indicated that all tested samples contained organochlorine and organophosphate pesticide residues at levels below the 5 µg/kg threshold (Tables 3 and 4).

Table 3- Concentration of organochlorine pesticide residues in farmed beluga caviar determined by GC-MS/MS

Organochlorine pesticide	Detection limit (µg/Kg)	MRL(µg/Kg)	Result (µg/Kg)
HCB	5	10	**<10**
HCH alpha	5	10	**<10**
HCH beta	5	10	**<10**
HCH gamma(Lindane)	5	10	**<10**
Heptachlor	5	10	**<10**
Heptachlore epoxyde	5	10	**<10**
Aldrine	5	10	**<10**
Chlordane cis	5	10	**<10**
Chlordane trans	5	10	**<10**
Endrin	5	10	**<10**
Methoxychlore	5	10	**<10**
DDT isomers	5	10	**<10**
Pendimethaline	5	10	**<10**
Dieldrin	5	10	**<10**
Endosulfan alpha	5	10	**<10**

Endosulfan beta	5	10	**<10**
Endosulfan sulphate	5	10	**<10**
Dicofol	5	10	**<10**
Chlorothalonil	5	10	**<10**

Table 4- Concentration of organophosphate pesticide residues in farmed beluga caviar

Organophosphate pesticide	**Method**	**Detection limit (µg/Kg)**	**MRL(µg/Kg)**	**Result (µg/Kg)**
Trichlorfon	LC/MS/MS	5	10	**<10**
Malathion	GC/MS/MS	5	10	**<10**
Chlorpyrifos	LC/MS/MS	5	10	**<10**
Phoxim	LC/MS/MS	5	10	**<10**
Profenofos	LC/MS/MS	5	10	**<10**
Diazinon	LC/MS/MS	5	10	**<10**
Fenitrothion	GC/MS/MS	5	10	**<10**

The findings of this revealed that dye residues were consistently lower than the stringent threshold of 0.2 µg/Kg, indicating that the product is free from significant artificial coloring and poses no safety concerns regarding dye contamination (Table 5).

Table 5- Concentration of dye residues in farmed beluga caviar by LC-MS/MS

Dye	**Detection limit (µg/kg)**	**MRL (µg/kg)**	**Result (µg/Kg)**
Malachite green	0.2	0.5 (Sum of MG&LMG)*	**<0.2**
leucomalachite green	0.2		**<0.2**
Crystal violet	0.2	0.2	**<0.2**
Leuco crystal violet	0.2	0.2	**<0.2**

According to the data in Table 6, LC-MS/MS analysis confirmed that any antibiotic residues present in the samples were below the detection threshold and compliant with Commission Regulation (EU) No 37/2010.

Table 6- Concentration of antibiotic residues in farmed beluga caviar by LC-MS/MS

Antibiotic	**Detection limit (µg/kg)**	**Result (µg/Kg)**	**MRPL (ppb)**
Oxytetracycline	25	<25	**25**
Tetracycline	25	<25	**25**
Chlortetracycline	25	<25	**25**
Doxycycline	25	<25	**25**
Ciprofloxacine	15	<15	**15**
Enrofloxacine	15	<15	**15**
Danofloxacine	25	<25	**25**
Difloxacine	75	<75	**75**
Marbofloxacine	40	<40	**40**
Sarafloxacine	10	<10	**10**
Erythromycine	50	<50	**50**
Sulfadiazine	25	<25	**25**
Sulfadimethoxine	25	<25	**25**
Sulfachloropyridazine	25	<25	**25**
Sulfamethoxypyridazine	25	<25	**25**
Sulfaquinoxalin	25	<25	**25**
Sulfadimidine	25	<25	**25**
Trimethoprime	15	<15	**15**
Florfenicol	15	<15	**15**
Norfloxacin	5	<5	**5**
Nalidixic Acid	4	<4	**4**
Cefuroxime	5	<5	**5**

4.Discussion

High concentrations of heavy metal residues in caviar above the maximum residue limits should be considered as a serious risk to consumers. The results of this study indicated that the levels of heavy metals in the analyzed matrix were below the limit of detection. Similar results were reported by Fath El-Bab and Seadawy (2006), who recorded average heavy metal levels in caviar samples as follows: Pb (0.064 ppm), Hg (0.162 ppm), and Cd (0.052 ppm) [19]. Adel et al. (2026) measured toxic elements (cadmium, lead, chromium, arsenic, mercury) in caviar from farmed Siberian sturgeon (*Acipenser baerii*) in Tehran Province, Iran. The results indicated that toxic element levels were minimal and complied with international regulatory standards [20]. Hosseini et al. (2013) evaluated the concentrations of Ba, Se, Hg, and Sn in the caviar of wild *Acipenser persicus*. Their findings indicated that, except for mercury, the mean levels of the other metals were considerably under the permissible limits, and thus not harmful for human consumption [21]. Ni et al. (2021), detected four heavy metals in the samples, including cadmium, lead, copper, and mercury. Furthermore, they reported the presence of copper and mercury in all analyzed samples; notably, lead exhibited the highest prevalence (77.4%), followed by cadmium (34.0%) [22].

According to the results of this study, the dye residues were below 0.2 μg/Kg. Similar findings were noted by Kirschbaum et al. (2006), who reported that genuine *Sevruga Malossol* caviar from *Acipenser sturio* L. contained no detectable colorant [23]. However, they detected and E 151 E 110 in German caviar made from lumpfish. Consistent with our findings, Rejczak and Tuzimski (2017) reported that the concentrations of dyes in fish roe specimens (ranging from 67.3 to 237.8 μg/g) were below the maximum permitted level of 300 μg/g set by Commission Regulation (EC) No 94/36/EC (1994) for this food category [24].

Pesticides are broken down slowly in the environment, showing resistance to both hydrolysis and biodegradation. In the present study, the pesticides levels were lower than 5 μg/kg. Multiple studies have consistently reported higher levels of organochlorine compounds in Black Sea caviar in comparison with specimens from the Caspian Sea [25, 26]. Wang et al. (2008) noted that Romanian *Huso huso* caviar had the highest ΣPCB concentration (388 ng/g lipid weight) among samples from seven countries, including Iran, Azerbaijan, France, Kazakhstan, Russia, Romania and Moldova [8].

Despite the widespread use of antibiotics, analysis of the samples in this study revealed that antibiotic residue levels were below the detection limit. In contrast, Ni et al. (2021) identified ten antibiotics, including oxytetracycline, ampicillin, ciprofloxacin, chloramphenicol, pefloxacin, sulfapyridine, sulfisomidine, enrofloxacin, sulfadiazine, and ofloxacin, in 106 seafood samples from Shanghai, China. Chloramphenicol showed the highest prevalence (47.2%), followed by ampicillin (31.1%) and ciprofloxacin (15.1%). Conversely, the occurrence of pefloxacin (0.9%), sulfapyridine (1.9%), and sulfisomidine (1.9%) was markedly lower [22].

5. Conclusion

Ensuring that luxury food products such as caviar are both safe and of high quality is important not only owing to their economic significance but also because of their potential direct effects on consumer health. Advanced analytical techniques, including ICP-MS, LC-MS/MS, and GC-MS/MS, confirmed that the levels of Pb, Hg, and Cd were below 10 μg/kg, antibiotics in line with Commission Regulation (EU) No 37/2010, dye residues were lower than 0.2 μg/kg, and the pesticide residues were below 5 μg/kg. The findings of this study, based on caviar samples collected from major Iranian aquaculture facilities during the 2024–2025 production cycle, demonstrate that the levels of all tested contaminants were below the analytical limits of detection (LOD), therefore posing no health risks to consumers.

Ethical Considerations

Not Applicable.

Data availability

All data analyzed during this study are included in this article.

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This study was extracted from the PhD dissertation of Hadi Tabarraee, approved by the Department of Food Hygiene, Faculty of Veterinary Medicine, Islamic Azad University, Science and Research Branch, Tehran, Iran.

Authors' contributions

Conceptualization, study design and experiments: Hadi Tabarraee; Abbasali Motallebi; Data acquisition: Hadi Tabarraee; Project administration, technical, and material support, data analysis, interpretation Amir Ali Anvar; Afshin Akhondzadeh Basti; Writing the original draft: Hadi Tabarraee; Review and editing: Abbasali Motallebi; Amir Ali Anvar; Maryam Tala

Conflict of interest

The authors declared no conflict of interest.

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References:

[1]. Anaduaka EG, Uchendu NO, Asomadu RO, Ezugwu AL, Okeke ES, Ezeorba TPC. Widespread use of toxic agrochemicals and pesticides for agricultural products storage in Africa and developing countries: Possible panacea for ecotoxicology and health implications. Heliyon. (2023);9(4). [DOI: 10.1016/j.heliyon.2023.e15173]

[2]. Onofri L, Pulcini D, Martini A, Martinoli M, Napolitano R, Tonachella N, et al. Economic Analysis of Sturgeon Farming and Caviar Production: A Case Study of an Italian Fish Farm. Water. (2024);16(18):2618. [DOI: 10.3390/w16182618]

[3]. Da Silva MR, Noguera PM, Debeuf B, Petersen MA, Loos HM, Buettner A. Aroma profiling and volatile fingerprinting of commercial caviar (*Acipenser baerii* and *Acipenser gueldenstaedtii*). LWT. 2025:118261. [DOI: 10.1016/j.lwt.2025.118261]

[4]. Mashroofeh A, Bakhtiari AR, Pourkazemi M. Distribution and composition pattern of polycyclic aromatic hydrocarbons in different tissues of sturgeons collected from Iranian coastline of the Caspian Sea. Chemosphere. (2015);120:575-83. [DOI: 10.1016/j.chemosphere.2014.09.071]

[5]. Ustaoğlu S, Okumuş İ. The Sturgeons: Fragile species need conservation. Turk J Fish Aquat Sci. (2004);4(1). [DOI: 10.4194/trjfas.2004.01.01]

[6]. Bledsoe G, Rasco B. Caviar and fish roe. Handbook of food science, technology, and engineering. (2006);135:161-9. [DOI:10.1080/10408690390826545]

[7]. Deák G, Holban E, Sadîca I, Jawdhari A. Sturgeon parasites: A review of their diversity and distribution. Diversity. (2024);16(3):163. [DOI: 10.3390/d16030163]

[8]. Wang W, Batterman S, Chernyak S, Nriagu J. Concentrations and risks of organic and metal contaminants in Eurasian caviar. Ecotoxicol Environ Saf. (2008);71(1):138-48. [DOI: 10.1016/j.ecoenv.2007.06.007]

[9]. Kazangeldina Z, Izteliyeva R, Saez AC, Baybolova L, Kuzembayeva G. Improvement of safety assessment and quality control of fish products [eg, caviar, caviar of the perch family (Percidae)] based on traceability system. Food Sci Technol. (2022);42:e62922. [DOI: 10.1590/fst.62922]

[10]. Khalifa HO, Shikoray L, Mohamed M-YI, Habib I, Matsumoto T. Veterinary drug residues in the food chain as an emerging public health threat: Sources, analytical methods, health impacts, and preventive measures. Foods. (2024);13(11):1629.[DOI: 10.3390/foods13111629]

[11]. Mashroofeh A, Bakhtiari AR, Pourkazemi M, Rasouli S. Bioaccumulation of Cd, Pb and Zn in the edible and inedible tissues of three sturgeon species in the Iranian coastline of the Caspian Sea. Chemosphere. (2013);90(2):573-80. [DOI: 10.1016/j.chemosphere.2012.08.034]

[12]. Sobhanardakani S, Tayebi L, Hosseini SV. Health risk assessment of arsenic and heavy metals (Cd, Cu, Co, Pb, and Sn) through consumption of caviar of *Acipenser persicus* from Southern Caspian Sea. Environ Sci Pollut Res. (2018);25(3):2664-71. [DOI: 10.1007/s11356-017-0705-8]

[13]. Hight SC, Cheng J. Determination of total mercury in seafood by cold vapor-atomic absorption spectroscopy (CVAAS) after microwave decomposition. Food Chem. (2005);91(3):557-70. [DOI: 10.1016/j.foodchem.2004.10.004]

[14]. Erdogrul Ö, Covaci A, Schepens P. Levels of organochlorine pesticides, polychlorinated biphenyls and polybrominated diphenyl ethers in fish species from Kahramanmaras, Turkey. Environ Int. (2005);31(5):703-11. [DOI: 10.1016/j.envint.2005.01.002]

[15]. Pihlström T, Fernández-Alba AR, Amate CF, Poulsen ME, Hardebusch B, Anastassiades M, et al. Analytical quality control and method validation procedures for pesticide residues analysis in food and feed . Sante. (2021);11312(v2). SANTE 11312/2021

[16]. Sapozhnikova Y. Rapid Sample Preparation and Fast GC–MS-MS for the Analysis of Pesticides and Environmental Contaminants in Fish. LCGC Europe. (2014).

[17]. Hurtaud-Pessel D, Couëdor P, Verdon E, Dowell D. Determination of residues of three triphenylmethane dyes and their metabolites (malachite green, leuco malachite green, crystal violet, leuco

crystal violet, and brilliant green) in aquaculture products by LC/MS/MS: First action 2012.25. J AOAC Int. (2013);96(5):1152-7. [DOI: 10.5740/jaoacint.13-142]

[18]. Yipel M, Kürekci C, Tekeli IO, Metli M, Sakin F. Determination of selected antibiotics in farmed fish species using LC-MS/MS. Aquac Res. 2017;48(7):3829-36. [DOI: 10.1111/are.13209]

[19]. Fath el-bab G, Seadawy H. Quality characteristics of markerted fish roe and caviar. Vet Med J Giza. 2006;54(3):595-610. [DOI: 10.21608/vmjg.2006.379781]

[20]. Adel M, Sakhaei F, Hassanabadi M, Impellitteri F, Raeisi A, Faggio C. Bioaccumulation of Trace Metals and Consumer Health Risk Evaluation in Farmed *Acipenser baerii* Caviar From Iran. J Appl Toxicol. (2026). [DOI: 10.1002/jat.70078]

[21]. Hosseini S, Sobhanardakani S, Navaei MB, Kariminasab M, Aghilinejad S, Regenstein J. Metal content in caviar of wild Persian sturgeon from the southern Caspian Sea. Environ Sci Pollut Res. (2013);20(8):5839-43. [DOI: 10.1007/s11356-013-1598-9]

[22]. Ni L, Chen D, Fu H, Xie Q, Lu Y, Wang X, et al. Residual levels of antimicrobial agents and heavy metals in 41 species of commonly consumed aquatic products in Shanghai, China, and cumulative exposure risk to children and teenagers. Food Control. (2021);129:108225.[DOI:10.1016/j.foodcont.2021.108225]

[23]. Kirschbaum J, Krause C, Brückner H. Liquid chromatographic quantification of synthetic colorants in fish roe and caviar. Eur Food Res Technol. 2006;222(5):572-9. [DOI: 10.1007/s00217-005-0157-0]

[24]. Rejczak T, Tuzimski T. Application of high-performance liquid chromatography with diode array detector for simultaneous determination of 11 synthetic dyes in selected beverages and foodstuffs. Food Analytical Methods. (2017);10(11):3572-88. [DOI: 10.1007/s12161-017-0905-3]

[25]. Krüger A, Pudenz S. Chlorinated hydrocarbon pollution in caviar samples. IInternat. Rev. Hydrobiol. (2002);87(5-6):637-44. [DOI: 10.1002/1522-2632(200211)87:5/6<637::AID-IROH637>3.0.CO;2-G]

[26]. Wirth M, Kirschbaum F, Gessner J, Krüger A, Patriche N, Billard R. Chemical and biochemical composition of caviar from different sturgeon species and origins. Food/Nahrung. (2000);44(4):233-7. [DOI: 10.1002/1521-3803(20000701)44:4<233::AID-FOOD233>3.0.CO;2-1]