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Human Consumption of Non-Native Species in a Circular Economy: Determination of Persistent Organic Pollutants in the Invasive Signal Crayfish from a Baltic Coastal River and Its Assessment for Consumption

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Abstract: A circular economy aims at decoupling value creation from waste generation and resource use. The signal crayfish *Pacifastacus leniusculus* is kept worldwide in aquaculture and after escaping into the wild, may further be used for human consumption rather than eradicated and used for purposes such as fertilizing fields. The level of contamination by two groups of persistent organic pollutants (POPs), polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs), in non-native signal crayfish from a Baltic coastal river, was measured in two locations (under anthropogenic pressure and semi-natural pressure) to understand whether its consumption might be a threat to human health. Concentrations of indicators and total compounds of POPs in the edible parts of crayfish (muscular tissue of crayfish) with potential human health risks were determined. The levels of concentrations of POPs meet the requirements of Regulations (EU) No. 836/2011 and No. 1259/2011 for the consumption of crustaceans. Our results also indicate no significant public health risk caused by consumption of the signal crayfish (hazard quotients (HQ) < 1). The results show that the bioaccumulation of POPs depends on the species' traits and environment.

Keywords: human health risk assessment; circular economy; consumption pattern; invasive alien species management; food security

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1. Introduction

A circular economy keeps materials and products in circulation for as long as possible, reduces material use, redesigns materials and products to be less resource intensive, and recaptures "waste" as a resource [1]. Improvement of waste management is a key approach in the circular economy concept [2]. In this sense, we can consider the utilization of the invasive alien species (IAS) for human consumption. According to EU legislation [3], established IAS should be eradicated, killed, and eliminated (in the process of waste generation). However, we propose to recognize the signal crayfish as a food resource and to use captured crustaceans for human consumption.

The signal crayfish *Pacifastacus leniusculus* (Dana, 1852) is an attractive commercial species worldwide. It was introduced from North America to Sweden in the 1960s, and later to other European countries including Poland. This species has biological parameters predisposing it to aquaculture. It is a large crayfish with higher egg production and reaches sexual maturity earlier than the European crayfish [4–6]. It also has a higher growth rate compared to native species in Poland [7], and wide tolerance to the environmental conditions, such as water salinity up to 21 units and temperature up to 33 °C [8,9]. These abilities allow this crayfish to inhabit different habitats [8,10,11]. The high abundance of the signal crayfish in the Wieprza River system (Poland) is well documented [12,13] and is a consequence of escapes from local fish farms into the wild. This species is considered as an IAS in the area and poses a threat to the ecosystem and other species [13].

The Convention on Biological Diversity (CBD) [14] requires signatory states to eradicate alien species that threaten ecosystems, habitats, or species. The European Union (EU) Regulation on IAS (EU Regulation 1143/2014) [3] (EU, 2014) also requires measures to be taken by all Member States for the rapid eradication of new IAS, and the management of established ones of Union concern. Based on risk assessments of individual species, an Action List of IAS of EU concern has been adopted [3] (August 2016, updated in 2017) and the signal crayfish is on the list, due to their impacts on native aquatic species and habitats. Eradication of a population of an invasive alien signal crayfish potentially provides environmental, economic, and/or social benefits by preventing any further impacts and wider spread of the population. In our opinion, sustainable consumption of the signal crayfish seems to be more beneficial than elimination or eradication. Moreover, climate change is predicted to increase the abundance of non-native species and simultaneously decrease global food security [15,16].

Fish and shellfish are an important part of a healthy diet worldwide [17]. Crayfish are the world's third-largest crustacean species [18] and are a significant aquatic food [19]. Annual production of crustaceans in inland aquaculture reached above 3 million tons in 2016 [20]. However, the levels of halogenated contaminants in the potentially consumed signal crayfish from this area have not been assessed yet, but it is considered as a good supplement to the human diet due to high nutritional values (macro- and trace elements) [21]. The present paper fills this gap by providing data regarding food safety on the signal crayfish from a coastal Baltic river.

Persistent organic pollutants (POPs) such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) are organic compounds that are resistant to environmental degradation through chemical, biological, and photolytic processes. POPs are global pollutants, widely distributed, and may be transported over long distances [22]. They are ubiquitous pollutants in aquatic systems and are characterized by low water and high lipid solubility, leading to their bioaccumulation in fatty tissues of organisms [23]. Due to their potential toxicity to wildlife and bioaccumulation in organisms, POPs may cause chronic diseases, including cancer (e.g., [24]). Therefore, their level in food is an important parameter determining the threat to human health. While the quantity of the PAHs and PCBs are often determined in different aquatic biota (e.g., [25,26]), the levels of indicator chemicals within these POP groups as well as risk assessments caused by the consumption of particular aquatic organisms are relatively rare [27] (Windsor et al., 2019).

PAHs generally occur in complex mixtures, which may consist of hundreds of compounds. The Environmental Protection Agency of the United States of America (US EPA) recommended in 1970 the monitoring of a set of 16 PAHs which are frequently found in environmental samples. In 2002, the European Commission's Scientific Committee on Food (SCF) identified 15 PAHs as of major concern to human health (referred to later as the 15 SCF PAHs) [28]. These 15 SCF PAHs should be monitored to enable long-term exposure assessments and to verify the validity of the use of the concentrations of benzo[a]pyrene as a marker for a "total-PAH content" [29]. Three years later, the European Union (EU) recommended research on the occurrence of these 15 PAHs in food [29]. When the European Food Safety Authority (EFSA) invited the EU Member States to collect data on the occurrence of PAHs in food in 2006, benzo[c]fluorene was added to the 15 SCF PAHs. This merged set is now referred to as the 15 + 1 EU priority PAHs [30]. According to these recommendations, we determined 15 + 1 EU PAHs: naphthalene, acenaphtylene, acenapthtene, fluorine, phenanthrene, anthracene, fluoranthene, pyrene, benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, indeno(1,2,3-cd)pyrene, dibenzo(a,h)anthracene, and benzo(g,h,i)perylene. To manage health risks by consumption of the organisms contaminated by POPs, the US EPA approach is commonly applied. PCBs also occur in complex mixtures which may consist of hundreds of congeners.

We hypothesized that there are differences between concentrations of POPs in the signal crayfish muscle tissue collected in two areas: modified environment and semi-natural environment. Previous studies indicated that crayfish in streams are affected to a higher degree by pollutants in the catchment area than in the lakes, where internal processes govern the uptake of pollutants in crayfish [31]. The distribution of POPs in the crayfish from the river was unknown.

The objectives of this study are:

(1) to determine concentrations of persistent organic pollutants (PAHs, as above, and PCBs: 28, 52, 101, 118, 138, 156, 180) in the signal crayfish,
(2) to determine the levels of PAH4 and PCB6 and compare these values to the permitted maximum level in food following requirements of Regulations (EU) No. 835/2011 and No. 1259/2011 [32,33],
(3) to evaluate hazard quotients (*HQ*),
(4) to calculate consumption limits for carcinogenic and noncarcinogenic health effects.

2. Materials and Methods

2.1. Sampling Strategy

Crayfish were collected during summer at two different stretches of the River Wieprza system (Poland). The first sampling site was located close to the Baltic Sea (Figure 1). The second was located on the River Studnica in the upstream, semi-natural part of the river system. Crayfish were caught using the "Pirate" crayfish traps (Bock-Ås, Parainen, Finland), which are commonly used for crayfish sampling [34]. They were also collected by hand [35] at the River Studnica to increase the sample size. Crayfish were transported frozen and stored in a freezer at −20 °C until analysis in the laboratory.

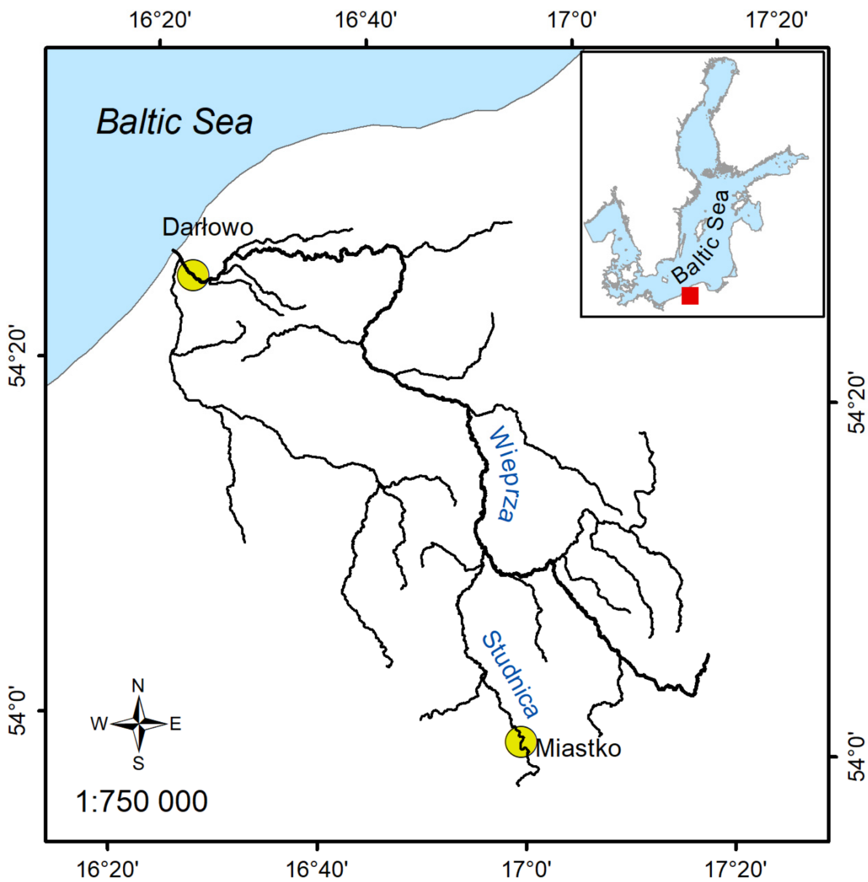

Figure 1. Sampling sites at the River Wieprza and its tributary.

2.2. Characteristics of the Study Area

The sampling sites were located in areas with different levels of anthropogenic pressure. The first, in Darłowo, was in the Lower Wieprza River, about 3 km from the river mouth (Figure 1), in the area where pollutants from the upper catchment are concentrated. The main potential sources of POPs in the Wieprza catchment area are chemicals used as lubricants in three hydroelectric power plants located in the middle section of the main river and in weirs, compounds used and emitted by vehicles, and water from wastewater treatment plants loaded with residues of substances used in the production of agricultural machines, and other processes. The second sampling site was located on the river upstream of the town of Miastko, on the River Studnica, in a semi-natural environment affected by agriculture, fish farming, and fishing. The distance between the two sites was about 70 km.

2.3. Laboratory Analysis

2.3.1. Preparation of the Material for Analysis

In the laboratory, the total length was determined by measuring the thawed specimen from the tip of the head to the telson using digital calipers [36]. After removal of surface water with filter paper, the wet mass was determined using a Mettler Toledo XS 205 balance with an accuracy of 0.001 g. PAH and PCB concentrations were determined in crayfish muscular tissue (the culinary used part of crayfish), which was cut from the carapace with a scalpel. The carapace was then dissected lengthwise and the tissue was collected for further analysis.

2.3.2. Sample Processing and Analysis

Crayfish muscle tissue was freeze-dried to a constant mass. The tissue was then homogenized in a mortar.

PAHs were analyzed according to the recommendation of HELCOM [37]. Subsamples of 5 g of dry material were Soxhlet-extracted with hexane/acetone (1:2, *v*/*v*) for 12 h. The extracts were evaporated under N_2 gas stream to about 1 cm^3 volume and purified on a column containing silica gel (6 mL, 1000 mg) and eluted with dichloromethane (8 mL). The eluate was concentrated to 1 cm^3 volume under N_2 gas stream.

PCBs were analyzed according to Bolałek [38]. Subsamples of 5 g of dry material were Soxhlet-extracted with hexane/acetone (1:2, *v*/*v*) for 12 h. The extracts were purified on a column containing two layers of silica gel with K_2CO_3 and silica gel with H_2SO_4 (1000 g each) and eluted with dichloromethane/hexane (5:95, *v*/*v*) (2 × 5 mL). The eluate was evaporated and dissolved in isooctan (1 mL).

Gas chromatography-mass spectrometry (GC-MS) analysis: The concentration of sixteen PAH compounds (naphthalene, acenaphtylene, acenaphtene, fluorene, fluoranthene, anthracene, fenanthrene, pyrene, benzo(a)anthracene, chrysene, benzo(a)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, indeno(1,2,3,cd)pyrene, dibenzo(a,h) anthracene, and benzo(g,h,i)perylene) were analyzed by GC–MS Hewlet Packard 6890 with mass selective detector 5973. A chromatographic column—Rxi-5ms (30 m; 0.32 mmID; 0.25 µm df) (Restek GC Columns)—was used. Temperature program PAH temperature 50–120 °C (50 °C/min), 120–300 °C (5 °C/min), 300 °C (10 min) (analysis time 48 min) was applied.

The concentrations of seven PCBs (PCBs 28, 52, 101, 118, 138, 153, and 180) were analyzed by GC–MS Hewlet Packard 6890 with mass selective detector 5973. A chromatographic column—Rxi-5ms (30 m; 0.32 mmID; 0.25 µm df) (Restek GC Columns)—was used. Temperature program PCB temperature 80–280 °C (10 °C/min), 280 °C (10 min) (analysis time 30 min) was applied.

Multilevel calibration and internal standards were used to determine POP concentrations. PAH mixture (Ultra Scientific, Santa Clara, CA, USA), and PCB mix 3 (Dr. Ehrenstorfer) were used.

Expression of results: The concentrations of sixteen PAHs (naphthalene, acenaphtylene, fluorine, phenanthrene, anthracene, fluoranthene, pyrene, benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, indeno(1,2,3-cd)pyrene, dibenzo(a,h)anthracene, and benzo(g,h,i)perylene) and of seven PCBs (PCBs 28, 52, 101, 118, 138, 156, and 180) were expressed in mg kg^{-1} on a dry mass sex basis.

Limits of detection (LOD) were calculated as a concentration of analyzed substances in carrier gas, which give a signal twice as large as noise level. LOD were 0.1 ng g^{-1} of PCBs and 1 ng g^{-1} of PAHs. Concentrations below the limits of quantification (LOQ) were equated to half of the LOQ.

Recoveries for PAH compounds varied between 83 and 116%.

Recoveries for all PCB compounds varied between 90 and 104%.

Quality Assurance/Quality Control: Analyses of POPs were performed according to technical standards, of US EPA 1668 [39], in the accredited laboratory of Maritime Institute in Gdansk, Department of Environmental Protection (Poland). QA/QC was performed through the analysis of procedural blanks, duplicate samples, and for each sample set with a relative standard deviation (RSD) below 15% for all detected compounds. POPs cause significant public and environmental health concerns, requiring quality control [40]. Polish-certified reference material Modas 5 Cod Tissue was used.

2.4. Health Risk Assessment of Consumption of Crayfish

Additionally, based on recommendation guidelines of Dougherty et al. [41] and US EPA [42], the health risk was assessed, taking into consideration both hazard quotients and risk-based consumption limits for either carcinogenic or noncarcinogenic health effects.

2.4.1. Hazard Quotient (*HQ*)

To assess the public health risk of exposure to POPs and through crayfish consumption, the hazard quotient (*HQ*) was calculated by comparing the average daily doses (*ADD*) of a pollutant taken in, with the reference doses (*RfD*) [42–45]. The *HQ* was calculated for PAH and PCB using Equation (1).

$$HQ = \frac{ADD}{RfD} \quad (1)$$

If $HQ < 1$ there is no significant risk, $HQ > 1$ represents a potential risk [42].

The *ADD* exposure level (intake) is expressed in milligram per kilogram per day and was calculated by the Equation (2).

$$ADD = \frac{Cm \times CR}{BM} \quad (2)$$

where

RfD = oral reference dose (mg kg^{-1} day^{-1})
ADD = average daily dose (mg kg^{-1} day^{-1})
BM = consumer body mass (70 kg)
Cm = measured concentration of chemical contaminant in fish (mg kg^{-1})
CR = mean daily crayfish consumption rate (0.05 kg day^{-1})

2.4.2. Risk-Based Consumption Limits

Based on US EPA [42], two equations were used for deriving crayfish daily consumption limits for both carcinogenic (Equation (3)) and noncarcinogenic (Equation (4)) health effects. To calculate consumption limits for carcinogenic effects, it is necessary to specify an acceptable lifetime risk level (*ARL*). The appropriate risk level was calculated as a risk level of 1 in 100,000 (10^{-5}).

carcinogenic health effect

$$CR_{lim} = \frac{ARL \times BM}{Cm \times CSF} \quad (3)$$

noncarcinogenic effect

$$CR_{lim} = \frac{RfD \times BM}{Cm} \quad (4)$$

where

CR_{lim} = maximum allowable crayfish consumption rate (kg d^{-1})
ARL = maximum acceptable individual lifetime risk level (unit-less)
BM = consumer body mass (70 kg)
Cm = measured concentration of chemical contaminant in crayfish (mg kg^{-1})
CSF = cancer slope factor (mg kg^{-1} day^{-1})
RfD = oral reference dose (mg kg^{-1} day^{-1}).

Cancer slope factor and oral reference dose were obtained from the US EPA Integrated Risk Information System for POP contaminants [46].

2.5. Statistical Analysis

The statistical analyses were performed using STATISTICA 12.0 Software (Statsoft, Kraków, Poland). Non-parametric Mann–Whitney U test was used to determine the statistical significance of differences between concentrations of POPs in the signal crayfish at different sampling sites. Use of a non-parametric test was necessary because the sizes of analyzed samples were not sufficiently large to run a parametric test (e.g., multivariate analysis) of all contaminants and assess the significance of different POP compound concentrations in the signal crayfish at different sampling sites.

3. Results

3.1. Persistent Organic Pollutants (PAHs and PCBs) in the Signal Crayfish

In total, 86 specimens of the signal crayfish (R. Wieprza, $n = 45$; R. Studnica, $n = 41$) were used in the analysis of persistent organic pollutants. The mean concentrations of PAHs and PCBs were higher in the signal crayfish from the Lower River Wieprza than from the River Studnica (Table 1, Figure 1). However, concentrations of PAHs, as well as PCBs, in the signal crayfish showed no statistical differences between the sampling sites ($p > 0.05$). Among polycyclic aromatic hydrocarbons (PAHs), the highest mean concentrations in the crayfish abdomen had phenanthrene in the crayfish from the River Wieprza (0.0245 mg kg^{-1}) as well as from the River Studnica (0.019 mg kg^{-1}) (Figure 2). PCB 101 had the highest mean concentrations amongst compounds of the PCB group in both localities: in crayfish from the R. Wieprza (0.0019 mg kg^{-1}) and from the R. Studnica (0.0016 mg kg^{-1}) (Figure 3). PCB 180 had a relatively high mean concentration in crayfish muscle tissue in the R. Wieprza (0.00125 mg kg^{-1}).

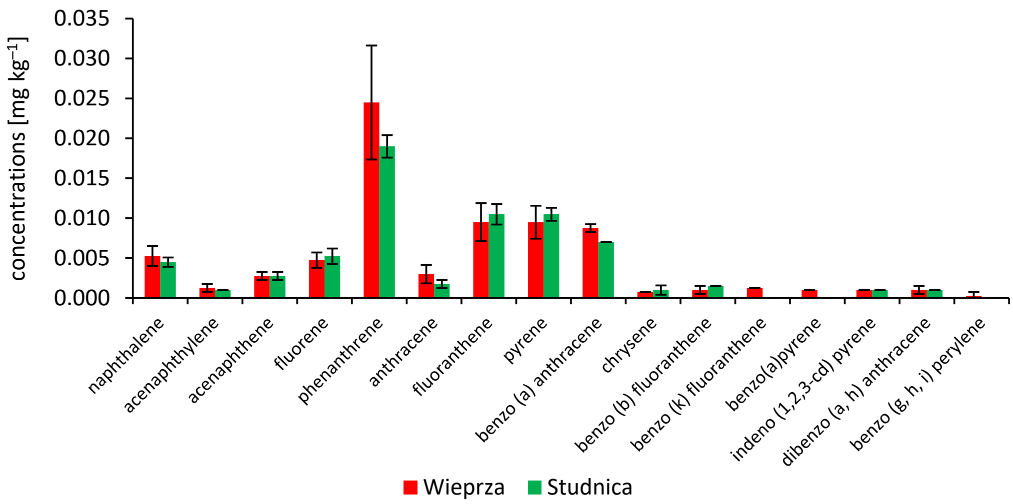

Figure 2. The levels of different polycyclic aromatic hydrocarbons (PAHs) with standard deviations (SD) in the signal crayfish from the Rivers Wieprza and Studnica.

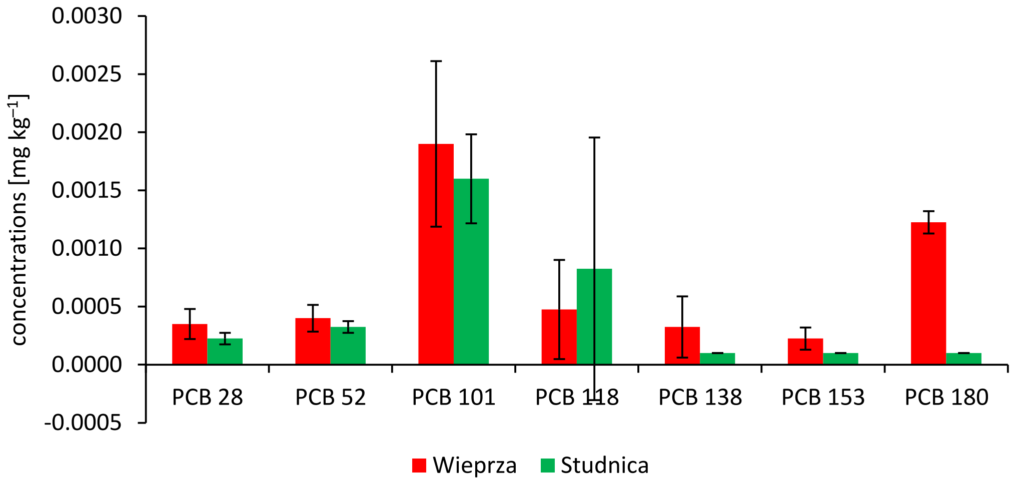

Figure 3. The levels of different polychlorinated biphenyls (PCBs) with standard deviations (SD) in the signal crayfish from the Rivers Wieprza and Studnica.

Table 1. The mean values of total length, dry mass, polycyclic aromatic hydrocarbons (PAH), and polychlorinated biphenyl (PCB) concentrations of the analyzed signal crayfish collected in the River Wieprza system.

Sampling Site	Total Length		Wet Mass		Concentrations of Persistent Organic Pollutants			
					PAHs		PCBs	
	Mean [mm]	SD	Mean [g]	SD	Mean [mg kg^{-1}]	SD	Mean [mg kg^{-1}]	SD
Wieprza	97.55	8.95	30.100	10.00	0.067	0.0568	0.0049	0.00108
Studnica	106.20	12.79	39.322	21.01	0.056	0.035	0.0032	0.00138

3.2. Human Health Risk Assessment Caused by Consumption of the Signal Crayfish from Different Sections of the River Wieprza and Its Tributary

The values of hazard quotients (*HQ*) were determined with the assumption that the exposed human population is safe when $HQ < 1$ [42]. In the present study, *HQ* was <1 in each case, indicating the health safety of the exposed population. Moreover, the carcinogenic and noncarcinogenic health risks were relatively low (Table 2).

Table 2. Hazard quotients (*HQ*) and carcinogenic and non-carcinogenic consumption rates (CR_{lim}) of the signal crayfish from the Rivers Wieprza and Studnica caused by polycyclic aromatic hydrocarbons (PAH) and polychlorinated biphenyls (PCB).

Persistent Organic Pollutants	Sampling Site	Hazard Quotient (*HQ*)	Carcinogenic Risk CR_{lim} [g d^{-1}]	Non-Carcinogenic Risk CR_{lim} [g d^{-1}]
PAHs	Wieprza	0.160 *	1.43 *	313 *
	Studnica	0.133 *	1.72 *	375 *
PCBs	Wieprza	0.175	71.5	286
	Studnica	0.114	109.38	437.5

* Values are based on known RfD and CSF for benzo[a]pyrene currently available in EPA's Integrated Risk Information System (IRIS) [46].

The level of the sum of four markers, PAH4 (benzo(a)pyrene, benz(a)anthracene, benzo(b)fluoranthene, and chrysene), was 4 μg kg^{-1} for R. Wieprza and 3 μg kg^{-1} for R. Studnica. Maximum levels for benzo[a]pyrene maintained to ensure comparability with historical data were 1 μg kg^{-1} for R. Wieprza and 1 μg kg^{-1} for R. Studnica. This means that the maximum levels of EU marker PAH4 (12 μg kg^{-1}) and of benzo[a]pyrene

(2 µg kg^{-1}) were not exceeded. The level of the sum of six indicators, PCB6, represents six congeners (PCB 28, 52, 101, 138, 153, and 180) in crayfish from both sampling sites (R. Wieprza, c = 4.05 ng g^{-1}; R. Studnica, c = 1.9 ng g^{-1}) and did not exceed the permissible level of PCB6 (75 ng g^{-1}) assessed by the EU Commission's Regulation [35] (Figure 4).

Benzo[a]pyrene is an indicator chemical for the PAHs, a chemical selected to represent the toxicity of a mixture of PAHs, because it is characteristic of other components in the mixture and has adequate dose–response data. The health risk values of the indicator chemical are coupled with exposure estimates for the mixture to estimate the health risk from the group PAHs [47].

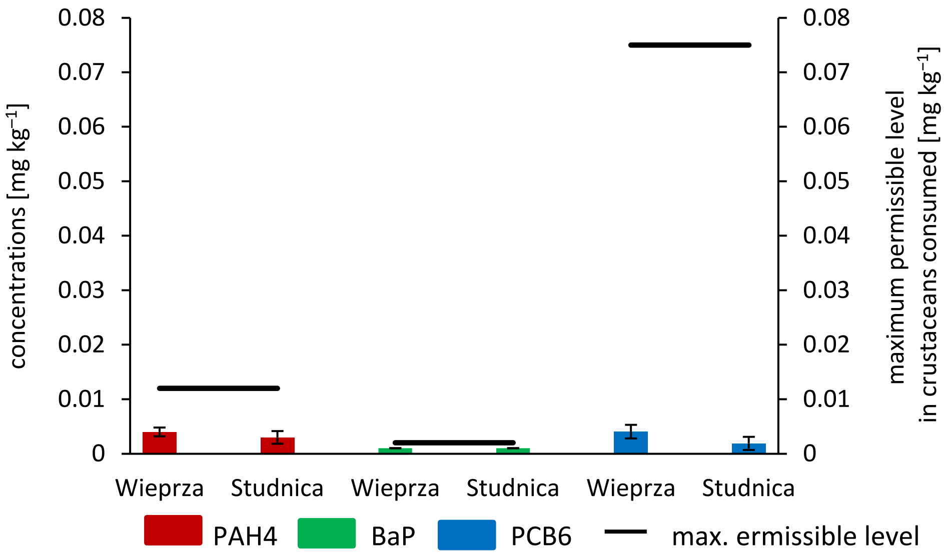

Figure 4. The levels of marker polycyclic aromatic hydrocarbons (PAH4), benzo[a]pyren (BaP), and indicator polychlorinated biphenyls (PCB6) in the signal crayfish collected from the Rivers Wieprza and Studnica and maximum permissible levels according to EU Regulations [32,33].

4. Discussion

According to the US EPA, PCBs are used in a variety of industrial processes (e.g., electrical transformers and capacitors, fluids, paint additives, carbonless copy paper, and plastics, and also are unintentionally produced during combustion). PAHs are produced when coal, oil, gas, wood, garbage, and tobacco are burned. Motor vehicle exhausts, cigarette smoking, wood smoke, and fumes from asphalt roads are common sources of PAHs in the environment. It is not surprising that in localities connected with human activities, POPs in the environment are expected. Although we predicted that POPs would not be detectable in the signal crayfish from the upper, semi-natural river section, our results showed that POPs may occur. Tanabe et al. [48,49] found that POPs were detectable in areas experiencing limited human activity (such as in Antarctica and the Arctic) due to atmospheric transport and deposition [50].

Based on the EU Commission's Regulation No. 835/2011 [32], the highest permissible level of the concentrations of PAH4 (benzo(a)pyrene, benz(a)anthracene, benzo(b)fluoranthene, and chrysene) in consumed crustaceans is 12 µg kg^{-1} (in our study it was equal to 4 µg kg^{-1} in the crayfish from the River Wieprza and 3 µg kg^{-1} in the crayfish from the River Studnica) (Figure 4). It should be mentioned that until 2008, benzo(a)pyrene was used as a marker for the occurrence of PAHs in foods. But, in 2008, the Scientific Panel on Contaminants in the Food Chain of the European Food Safety Authority (EFSA) concluded that benzo(a)pyrene alone was not a suitable marker for the occurrence of PAHs in foods and that a system of four markers (benzo(a)pyrene, benzo(a)anthracene, benzo(b)fluoranthene and chrysene) would be more suitable markers. Consequently, the Commission Regulation EU 835/2011 [32] amended Regulation (EC) 1881/2006 [31] in order to set maximum levels in specific foodstuffs for the sum of the four markers of PAHs. Maximum levels for benzo[a]pyrene were maintained to ensure comparability with historical data. Currently, maximum levels in food are specified for benzo[a]pyrene (BaP) and PAH4 [33] both in the crayfish from the R. Wieprza and the R. Studnica PAH4—they were not exceeded (Figure 4).

The calculated mean concentrations of all PAHs in muscular tissue of crayfish were higher than those found in smoked fish such as rainbow trout *Oncorhynchus mykiss* (Walbaum, 1792) (2.73), common carp *Cyprinus carpio* Linnaeus, 1758 (8.32), vendace *Coregonus albula* (Linnaeus, 1758) (6.45), and European eel *Anquilla anquilla* (Linnaeus, 1758) (3.65 µg kg^{-1}) [26]. However, the total amount of contaminants in the crayfish may decrease because lipids and lipophilic compounds are partially removed during the cooking process [25,51]. Among PAHs, the phenanthrene concentrations were especially high in crayfish collected close to the river mouth (R. Wieprza). Its concentrations were also higher than those of other polycyclic aromatic hydrocarbons in both sampling sites, due probably to the fact that it is one of the most abundant PAHs present [52,53]. Phenanthrene may cause cardiac dysfunction by decreasing extracellular Ca^{2+} influx into the cell, inhibiting K^+ efflux from the cardiomyocyte, and altering cardiac force and cardiac rhythm [54]. This substance might be carcinogenic, but its relative carcinogenic potential is extremely low, with a low oral toxicity and a tolerable daily intake (TDI) of 0.04 mg $kgbm^{-1}d^{-1}$ [55]. The concentrations of PAHs in the crayfish are lower in tails than in other parts of its body, e.g., in viscera. This suggests that eating only the tail tissue of the crayfish would yield significantly less carcinogenic risk than eating viscera, or the whole organism [56].

Concerning the concentrations of PCBs, the level for the sum of six indicators, PCB6, representing six congeners (PCB 28, 52, 101, 138, 153, and 180) [34], both in crayfish from the R. Studnica (c = 2.3 ng g^{-1}) and R. Wieprza (c = 4.2 ng g^{-1}) did not exceed the permissible level of 75 ng g^{-1} assessed by the EU Commission's Regulation [34]. Higher concentrations of all PCBs were found in other crustaceans from the Baltic Sea basins such as the Chinese mitten crab *Eriocheir sinensis* H. Milne Edwards, 1853 in the Gulf of Gdansk (289 ng kg^{-1}) or the spiny-cheek crayfish *Faxonius limosus* (Rafinesque, 1817) from the Vistula Lagoon (100 ng kg^{-1}) [26]. In contrast, a demersal fish, the round goby *Neogobius melanostomus* (Pallas, 1814) from the Gulf of Gdańsk, had concentrations of PCBs at a much lower level—6 ng kg^{-1} [26]. It is known that PCBs may exacerbate infectious diseases because they disturb the human immune and endocrine systems [57,58]. Among PCBs, PCB 101 in crayfish from the R. Wieprza and the R. Studnica and PCB 180 in crayfish muscle tissue from the R. Wieprza had relatively high concentrations. These PCBs are abundantly present in the environment and food and may have neurobehavioral effects (e.g., [59,60]). PCB 101 and PCB 180 increase the susceptibility to bacterial infection [61]. However, as determined in our study, concentrations of PCBs did not exceed permissible EU levels.

There was a lack of statistical differences between concentrations of POPs in the signal crayfish collected from the Lower Wieprza River and from the upstream section of the river system (River Studnica). We expected that persistent organic pollutants would not be detected in crayfish in the semi-natural area due to the lack or minimal level of local sources of POPs. But their occurrence in the signal crayfish may indicate that the biotransport of POPs is also possible. Specimens of the signal crayfish are characterized by high spatial activity in the river manifested through movement [62]. They may migrate in an upstream and downstream direction, crossing sediments contaminated by persistent organic pollutants. Many other migratory species, such as salmonids [63,64], transport POPs over long distances and may be biovectors of persistent organic pollutants from sources to remote areas. In this way, POPs may be detectable in organisms even living in areas where POPs have never been detected.

Previous studies showed that the life span of organisms can affect the bioaccumulation of pollutants in them [65]. In long-living species, such as crayfish, which can live for up to 20 years [66], the bioaccumulation may be higher than in the case of short-living organisms [65]. However, the signal crayfish is not exposed to POP pollutants as species at the higher trophic levels are, because during biomagnification, the accumulation of pollutants through trophic transfer along the food chain occurs [67]. Additionally, waterrespiring organisms (such as the signal crayfish) exhibit lower biomagnification than air-respiring organisms, which is related to differences in digestive tract physiology and body temperature [68].

Determined carcinogenic risk (CR_{lim}) represents the potential health risk associated with various types of cancer caused by the consumption of polluted signal crayfish meat. CR_{lim} for non-carcinogenic effects considers some adverse health effects, such as reproductive, neurodevelopmental, cardiovascular, and endocrine diseases [69]. The values of carcinogenic risk CR_{lim} (cancer risk over a lifetime), of PAHs and PCBs are lower than that of the non-carcinogenic risk (Table 2). Based on the US EPA approach, there is no significant public health risk caused by consumption of signal crayfish polluted by POPs, because the calculated hazard quotients (*HQ*) were lower than 1. However, the crayfish samples were tested in the raw, dry tissues, and after cooking treatment, the levels of contaminants in the consumed muscle tissue are lower [26,51]. Additionally, in Poland, the crayfish are considered as a delicacy and their consumption is occasional and at a low level compared with traditional sources of proteins such as meat and fish. According to Godfray et al. [70], the mean intake of processed meat in Western Europe is about 26.4 g d^{-1}. The mean fish consumption for the general population and recreational fishers amounted to 17.5 g d^{-1} [45]. In contrast, the crayfish are not sold in grocery stores in Poland, with the exception of the IKEA stores where they are seasonally sold. In the future, this may be changed because of the increasing demand for proteins. The World Health Organization recommends the consumption of 1–2 portions d^{-1} of lean meat, poultry, fish, or legumes in Poland [71]; therefore, alternative sources of proteins may become more popular amongst some consumers.

The signal crayfish may become a popular seasonal food locally served in Poland, as in some countries, e.g., Sweden [72]. The consumption of this species is a good way of utilizing 'unwanted' invaders in the natural environment and its suitability as a food has been confirmed [18,73]. Since signal crayfish threaten ecosystems by causing a decline of native species as well as modify the environment by burrowing into river and canal banks resulting in an increase in erosion [73], some action to reduce their number should be implemented. Campaigns towards increasing humans' consumption of this crayfish should accelerate the removal of this non-native species in the studied area [74,75]. Strategies to increase consumption of the signal crayfish should include subsidies for trapping in the River Wieprza catchment area, campaigns to encourage the use of this species, and lowering prices per unit.

In addition to the above actions, a program of monitoring the signal crayfish and native communities should be instigated with the cooperation of research institutes and local stakeholders responsible for nature conservation, water management, and fisheries.

This program should provide data on signal crayfish abundance, their recruitment, and an assessment of the effectiveness of harvesting efforts with social-economic effects.

5. Conclusions

The invasive signal crayfish from the River Wieprza may be used in a circular economy for human consumption, which is more beneficial than the typical eradication of the species and it may hasten the removal of this "unwanted" invader from the natural environment. Consumption of the signal crayfish from the River Wieprza is safe for humans. Based on requirements of Regulations (EU) No. 836/2011 and No. 1259/2011, there is no significant public health risk caused by the consumption of signal crayfish inhabiting the River Wieprza. Similarly to the US EPA approach, the public health risk caused by the consumption of signal crayfish polluted by POPs is not significant, because the hazard quotients (*HQ*) were lower than 1.

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