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Assessment of the mercury-selenium antagonism in rainbow trout fish

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27 **Abstract**

28 This study aims at the assessment of mercury (Hg)-selenium (Se) antagonism in fish. For this
29 purpose, rainbow trout fish (*Oncorhynchus mykiss*) were exposed to methylmercury (MeHg) under
30 controlled conditions, in the presence or absence of selenomethionine (SeMet) using an in-house
31 prepared diet (enriched with MeHg and SeMet at 0.2 µg/g and 5.0 µg/g, respectively). The total
32 duration of the exposure study was 3 months. Fish was sampled and analysed for total Se (Se_T) and
33 total mercury (Hg_T) content after 1, 2 and 3 months of exposure. Six feeding protocols were
34 compared, depending on the exposure type: (i) no MeHg nor SeMet exposure (control group); (ii)
35 exposure to SeMet solely; (iii) exposure to MeHg solely; (iv) exposure to both MeHg and SeMet;
36 (v) exposure first to MeHg during 1 month and then to SeMet during 2 months and (vi), exposure to
37 SeMet during 1 month and then to MeHg for 2 months. The levels of Se_T and Hg_T in the fish
38 (control and supplemented with MeHg/SeMet) were measured by inductively coupled plasma-mass
39 spectrometry (ICPMS).

40 Steadily (linear) bioaccumulation of MeHg in the fish muscle occurred when the fish were exposed
41 individually to this species during the period. The bioaccumulation of MeHg is diminished when
42 the fish are firstly exposed to SeMet and then to MeHg, hence indicating the MeHg detoxification
43 due to SeMet supplementation.

44

45

46 **Keywords:** Mercury; selenium; antagonism; rainbow trout fish; dietary exposure; ICP-MS

47

48 **1. Introduction**

49 The high nutritional value of fish makes it an ideal component of a healthy and balanced diet for
50 humans. However, some fish species accumulate substantial levels of trace toxic metals, such as
51 mercury (Hg) hence hampering the consumption of such diet (Cabanero et al. 2004). Actually, the
52 fish represents the main pathway (80-99%) of humans' exposure to Hg via methylmercury (MeHg)
53 species most commonly found in fish and which is considerably more toxic than its inorganic
54 precursor (Hg²⁺) (WHO 2008; Eagles-Smith et al. 2018).

55 Humans' exposure to MeHg poses a risk for their health especially due to its neurotoxic effects,
56 being considered a major public health concern by World Health Organization (WHO 2008). These
57 effects arise from its high biological membranes permeability, potent bioaccumulation, stability and
58 long-term elimination from tissues (Wang et al. 2003; EFSA 2012).

59 Fish is therefore a dietary product for which suitable measures should be taken to minimize the risks
60 related to Hg exposure (McEneff et al. 2017). It is worth to note that fish is also an important
61 contributor of selenium (Se) to humans, mostly as selenomethionine (SeMet), generally around 40–
62 50% of the total Se diet (Misra et al. 2012). Nevertheless, Se has a narrow threshold between
63 essentiality and toxicity and becomes toxic to fish at a slightly elevated level beyond the optimum
64 intake (Misra et al. 2012; Ralston et al. 2016).

65 Although Hg interaction with sulphur-containing proteins/enzymes in fish is relatively well
66 understood, the mechanism of its interaction with Se compounds such as selenoproteins is not
67 completely known. Nevertheless, it appears that Se species can play a role in Hg detoxification
68 hence mitigating the human exposure to MeHg contamination (Dang et al. 2011; Luque-Garcia et
69 al. 2013). The current evidence suggests that the protective effect of Se against Hg may be related
70 to the amount of Se available. It is generally accepted that the molar concentrations of Se and Hg in
71 protected tissues need to exceed a 1 : 1 stoichiometry to be effective (Gochfeld et al. 2021).

72 Underlying the central paradigm that Hg exposure is less hazardous when tissue Se is in (molar)
73 excess it is suggested that the Se protection occurs through Hg sequestration. Hg shows high

affinity for Se leading to HgSe precipitation, a species that seems to be metabolically inert (Raymond et al. 2020). In addition, it is suggested that the protective effect of Se depends on its availability for the selenoprotein synthesis (Manceau et al. 2021; Castriotta et al. 2020).

This study aims at the assessment of the dynamics of dietary MeHg in a fresh-water fish in the presence of SeMet, to understand the interactive effects of Se on Hg bioaccumulation as well as to elucidate the antagonistic relationship observed in other studies (Dang et al. 2011). For this purpose, an exposure study of dietary exposure to MeHg and SeMet of rainbow trout under various conditions such as exposure to MeHg and SeMet solely, simultaneously and sequentially, was carried out. The exposure study was carried out during a relatively long duration (3 months) to reflect the chronic exposure conditions (Ralston et al. 2009). The diet employed here prevented also acute, high exposure of fish with Hg and Se, which in the real world would happen only accidentally, as it was the case of MeHg poisoning in Minamata (Harada 1995). A novel method was also validated by using inductively coupled plasma-mass spectrometry (ICP-MS) for the simultaneous determination of trace and ultra-trace total Hg (Hg_T) and total Se (Se_T) in the muscle of the rainbow trout exposed to SeMet and MeHg.

2. Materials and Methods

2.1. Instrumentation

An ICP-MS iCAP Q (ThermoFisher Scientific, Courtaboeuf, France) equipped with a PFA standard nebulizer and a Teflon spray chamber was used for the determination of Hg_T and Se_T . Kinetic energy discrimination (KED) using helium (He) as a collision gas was employed throughout the study for interferences removal, namely the polyatomic interferences $^{40}Ar^{38}Ar^+$ and $^{38}Ar^{40}Ca^+$ on ^{78}Se isotope. The samples were digested using a closed microwave system (Multiwave 3000, Anton Paar, Courtaboeuf, France) equipped with a rotor for 80 mL quartz vessels.

ICP-MS measurement conditions were optimized daily by running short-term sensitivity and stability tests using the KED mode. Data were processed using ThermoFisher Scientific Qtegra software.

The optimum operating conditions of the iCAP-Q ICP-MS are summarized in Table 1.

Table 1. ICP-MS operating conditions for Se_T and Hg_T determination in fish.

Plasma power	1550 W
Reflected power	<5 W
Plasma gas flow (Ar)	14.0 L/min
Auxiliary gas flow (Ar)	0.8 L/min
Nebuliser gas flow (Ar)	1.0 ± 0.1 L/min (depending on daily optimisation)
KED gas flow (He)	5.0 mL/min
Spray chamber type & temperature	Quartz, concentric, 2.7 °C
Nebuliser type	PFA-ST Microflow
Monitored isotopes	⁷⁸ Se, ²⁰² Hg, ⁸⁹ Y, ¹⁸⁵ Re
Dwell time	0.1 s
Measurements number	5

102

103 **2.2. Chemicals and reagents**

All solutions were prepared using analytical reagent grade chemicals and ultrapure water (18.2 MΩ cm⁻¹, Millipore Milli-Q™, Merck Millipore, Saint Quentin in Yvelines, France). Suprapur HNO₃ (67% m/m) was purchased from VWR (Fontenay-sous-Bois, France). The standard stock solutions at 1000 mg/L of Hg, Se, Au, Re and Y were purchased from SCP Science (Courtaboeuf, France).

The intermediate solution of Se and Hg at 1.0 mg/L (available for one month when stored at 4-5 °C) was used for the daily preparation of the calibration solutions.

The tuning solution for the daily optimization of the ICP-MS consisted of Ba, Bi, Ce, Co, In, Li and U at 1.0 µg/L in HNO₃ 2% (v/v) and HCl 0.5% (v/v) (Tune B iCAP Q/RQ) and it was purchased from Thermo Fischer Scientific (Courtaboeuf, France).

The certified reference materials (CRMs) used in this study were ERM®-BB-422 (fish muscle) and ERM®-CE101 (trout muscle) from the European Joint Research Centre (JRC), DORM-4 (fish protein) from the National Research Council Canada and 7402-a (codfish tissue) from the National Metrology Institute of Japan and they were purchased from LGC Standards (Molsheim, France).

117 Ultrapure grade (99.9995%) argon and helium employed in ICP-MS were supplied by Linde
118 (Montereau, France).

119 High purity seleno-DL-methionine ($\geq 99\%$) and methylmercury chloride ($802 \mu\text{g/mL} \pm 2\%$) were
120 obtained, from Sigma-Aldrich (Saint-Quentin-Fallavier, France) and LGC Standards, respectively.

121 The fish feed used for the dietary exposure study was purchased from Nouvelles Vague, Wimereux,
122 France. Commercial dried pellets (T-PRIMA - 5 mm and semi-floating) were obtained from Le
123 Gouessant Aquaculture, Lamballe-Armor, France. The different enriched diets were prepared by
124 Nouvelle Vague company using an in-house developed process (based on vacuum technology)
125 allowing the enriching compounds (contained in 1% of an aqueous phase of an oil emulsion) to
126 achieve the pellets' core. The aim was to avoid the dispersion of MeHg and/or SeMet into the tank
127 water during fish feeding. For confirming that, Se_T and Hg_T levels were measured by ICP-MS in the
128 water solution in contact with the pellets. Once the optimum conditions were achieved, appropriate
129 amounts of control and supplemented (semi-floating) diet were produced, as follows:

130 (i) 5 kg of non-supplemented diet (pellets), coated with the emulsion solely (without MeHg or
131 SeMet);

132 (ii) 10 kg of diet supplemented with MeHg at a final concentration of 0.2 mg/kg;

133 (iii) 10 kg of diet supplemented with SeMet at 5.0 mg/kg;

134 (iv) 5 kg of diet supplemented with both MeHg (0.2 mg/kg) and SeMet (5.0 mg/kg).

135 The levels of Hg_T and Se_T in the fish diet (control and enriched with SeMet and MeHg,
136 respectively) were measured by ICP-MS using an accredited method (by COFRAC, the French
137 accreditation body), as reported by Chevallier et al. 2015; each diet was analysed in three
138 independent replicates to assess the average levels of MeHg and/or SeMet but also their
139 homogeneity. Hg_T levels measured in the control and MeHg-spiked diets were 0.052 ± 0.002
140 (RSD=3.6%) and $0.24 \pm 0.01 \text{ mg/kg}$ (RSD=4.1%), respectively, whereas Se_T were 0.95 ± 0.02
141 mg/kg (RSD=1.7%) and $5.41 \pm 0.36 \text{ mg/kg}$ (RSD=6.6%) in the control and the spiked diets
142 enriched individually with MeHg and SeMet. Se_T and Hg_T were 6.08 ± 0.02 (RSD=8.8%) and 0.26

143 ± 0.02 (RSD=6.3%), respectively, in the diet enriched with both MeHg and SeMet. The relative
144 standard deviation values (reported into the brackets) are < 10% in all cases, hence confirming the
145 satisfactory homogeneity of the diets used in this study.

146 147 **2.3. Fish**

148 In this study, 95 specific pathogen-free rainbow trout (*Oncorhynchus mykiss*, Walbaum, 1792)
149 including a mixture of males and females from the same genetic group were used. They were
150 handled at the protected and monitoring facilities of the Plouzané (France) laboratory of ANSES.
151 The fish were 18 months old, with a weight of 266 ± 20 g. They were fed once a day by using the
152 in-house prepared diet (dry pellets) at 1.5% of their body weight.

153 154 **2.4. Experimental exposure of fish to MeHg and SeMet species**

155 *2.4.1. Authorization to experiment and ethical aspects*

156 This exposure experiment was carried out in accordance with the European guidelines and
157 recommendation on animal experimentation and welfare (European Union Directive 2010/63). The
158 ANSES (Plouzané) laboratory is authorized to carry out experiments on fish in its facilities in
159 compliance with the Administrative Order No. E29-212-03 issued by the Prefecture of the Finistère
160 (France). This animal experimental procedure was also approved by the ethics committee on animal
161 experimentation ANSES/ENVA/UPC No. 16 and was authorized by the French Ministry of
162 Research, under the number APAFIS# 2019071109391903.

163 164 *2.4.2. Experimental design*

165 The experimental system consisted of six cylindrical 400 L resin tanks. In order to minimize the
166 tank effects, the same fresh river water flow at a flow of $0.5 \text{ m}^3/\text{h}$ was added to each tank to
167 maintain optimal water conditions for the fish throughout the experiment, such as: river water
168 temperature $\cong 12 \pm 2$ °C, oxygen saturation >80% of full air saturation, pH $\cong 8$ and water free of

169 nitrate and nitrite. Additionally, all the tanks were maintained in a natural light/dark cycle (10 h/14 h
 170 in winter, approximately) in a room with air volume changes every hour.

171 The fish were randomly distributed into the six tanks. After one week of acclimation, six groups
 172 were defined according to the daily diet supplemented with MeHg and/or SeMet for a duration of
 173 three months (from January 2020 to April 2020), as follows: control (G0), exposed to SeMet (G1),
 174 exposed to MeHg (G2), exposed simultaneously to SeMet and MeHg (G3), exposed initially to
 175 SeMet (one month) and then to MeHg (two months) (G4), and exposed initially to MeHg (one
 176 month) and then to SeMet (two months) (G5). The experimental scheme of the exposure study is
 177 provided in Fig. 1.

178 The dietary exposure to MeHg of the trout used in this study was chosen in agreement with the EC
 179 Regulation No. 1881/2006, which defines the maximum limit of Hg in fishery products, namely in
 180 the rainbow trout, at 0.5 mg/kg (wet weight, ww). The exposure level used in the study was set at
 181 40% below the EC maximum limit, to avoid mortality, taking into account the duration and the slow
 182 rate of Hg elimination from fish. The dietary exposure concentration for Se was fixed at an
 183 intermediary level in agreement with previous results from the literature (Misra et al. 2012; Sele et
 184 al. 2018; McEneff et al. 2017).

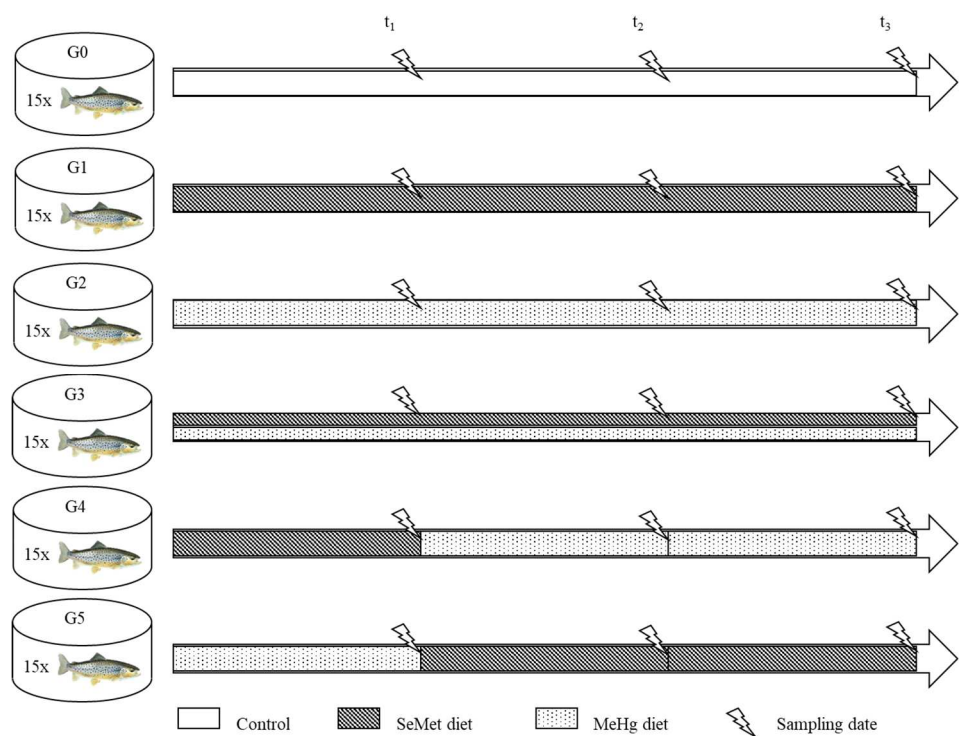


Fig. 1. Schematic representation of the *in vivo* exposure of rainbow trout to MeHg and SeMet.

2.5. Samples and sampling date

Five control fish were randomly sampled in the fish farming of ANSES just before the beginning of the trial (t_0). Amongst the fish exposed to MeHg and SeMet, five individuals of the corresponding exposure tank were sampled after one (t_1), two (t_2) and three (t_3) months of exposure. The fish were sacrificed by cutting their spinal cord; they were then measured and weighed. The fish muscles were sampled using a standardised cut. Scalpel blades were used to cut the entire fillet from the operculum to the tail, along the vertebral axis. The samples were kept on ice during sampling and transportation to the laboratory and then stored at $-20\text{ }^{\circ}\text{C}$ until analysis. The data related to the fish growth, including the global growth during the whole exposure study (t_3-t_0) are reported in Table 2.

Table. 2 Fish weight (g ww, mean \pm SD^a, n = 5) for each condition at the different sampling dates.

Exposure group	Fish weight (g)				Global growth ^a (g)
	t_0	t_1	t_2	t_3	
G0: Control		279.6 \pm 19.6	499.2 \pm 47.6	542.4 \pm 35.3	286.4
G1: SeMet		334.4 \pm 53.3	590.8 \pm 140.1	636.4 \pm 135.1	380.4
G2: MeHg		392.0 \pm 37.1	541.6 \pm 23.8	692.4 \pm 197.8	436.4
G3: SeMet and MeHg	256.0 \pm 22.7	395.6 \pm 44.0	512.8 \pm 107.5	725.6 \pm 72.2	469.6
G4: SeMet (one month) then MeHg (2 months)		361.2 \pm 58.5	492.0 \pm 136.6	640.0 \pm 92.8	384
G5: MeHg (one month) then SeMet (2 months)		376.8 \pm 38.7	510.8 \pm 64.0	667.2 \pm 72.1	411.2

^a standard deviation

^b weight at t_3 – weight at t_0

As can be seen from the Table 2, similar growth was observed for all exposure conditions, hence no corrections related to the growth process were necessary.

2.6. Analytical procedures

2.6.1. Sample preparation

The frozen fillets were thawed and then grounded and homogenized, prior to analysis. Approximately 0.5 g of samples were accurately weighed into a 80 mL quartz vessel and then thoroughly mixed and digested with a mixture of 3 mL of concentrated HNO_3 and 3 mL of ultrapure water using a closed microwave system; for this purpose, the blend was exposed to

microwave power of 800 W for 10 min, then increasing the power up to 1000 W and the sample kept in this condition during 10 min. Then the digests were quantitatively transferred into polypropylene tubes (50 mL) and then diluted to 50 mL with ultrapure water after the addition of the internal standards (Y for Se and Re for Hg at 2.0 µg/L).

210

211 *2.6.2. Determination of total Hg and Se by ICP-MS and the internal quality control assurance*

212 The quantification of Se_T and Hg_T in the fish digests was carried out by ICP-MS using the external
213 calibration in the range 1.0 to 20 µg/L. Several internal quality controls (IQC) were set up to
214 ensure the reliability of the results (Chevallier et al. 2015; Ghosn et al. 2020; Saraiva et al. 2021);
215 the data were valid only when all the acceptance criteria were satisfied.

216 The method trueness was assessed by analysing certified reference materials (CRM) in parallel with
217 each batch of samples. Each analysis run included also one digestion blank (to monitor possible
218 contaminations due to sampling preparation), one spiked sample (to assess the matrix effects), and a
219 mid-range standard solution containing Hg and Se (at 5.0 µg/L) that was analysed every ten
220 samples and also at the end of the sequence, to monitor instrumental drift; the data were validated
221 only when the deviation of the concentration of this control standard was ≤20% compared to the
222 theoretical value.

223 The variation of the IS (Y and Re) was also monitored to assess the instrumental drift and matrix
224 effects. In most cases, the recovery of IS was between 80% and 120%.

225 Finally, a solution of gold (Au) standard at 10 mg/L prepared in 6% HNO₃ (v/v) was used
226 throughout as a washing solution in between the analyses to reduce the memory effects related to
227 Hg analysis. Additionally, the elimination of the memory effects was assured by employing the
228 «Intelligent Rinse» mode of the ICP-MS. Briefly, this consists of the rinsing of the system after
229 each measurement as long as the analytes signal has not fallen below a certain threshold in terms of
230 intensity: in our case, this was set at 20 cps for ⁸²Se and at 800 cps for ²⁰²Hg.

231

232 *2.7. Data and Statistical analysis*

233 The bioaccumulation factor (BF, %) of Hg from the diet to the muscle of the rainbow trout fed with
234 MeHg supplemented diet (G2) was assessed. The same study was carried out for Se, i. e.,
235 calculation of the BF of Se from the diet to the fish muscle (%) in the fish group fed with SeMet
236 (G1), using the equation provided below.

$$237 \text{ BF (\%)} = ((C_{\text{muscle}} \times \text{BM})_{\text{three months}} - (C_{\text{muscle}} \times \text{BM})_{\text{control group}}) / (C_{\text{diet}} \times \text{FI}) \times 100$$

238 where:

239 BM, biomass muscle corresponding to 66% of the weight of the whole fish (mg);

240 C_{muscle} , Se or Hg mass fraction in muscle (mg/kg);

241 C_{diet} , Se or Hg mass fraction in diet (mg/kg);

242 FI, feed intake, corresponding to the amount of the diet consumed by the fish (1.5% body weight)
243 (mg).

244 The statistical data treatment was carried out using Statgraphics Centurion® software. All data sets
245 were first tested for normality (Shapiro–Wilk test). To detect significant differences among the
246 different dietary exposed groups, Hg_T and Se_T levels in muscle were analysed using one-way
247 analysis of variance (ANOVA) followed by the application of Tukey–Kramer HSD test with a p
248 < 0.05 . For all analyses, 95% confidence interval was applied with a level of $p < 0.05$ considered to
249 be significant. All data related to the fish analysis are reported as mean \pm standard deviation ($n = 5$).

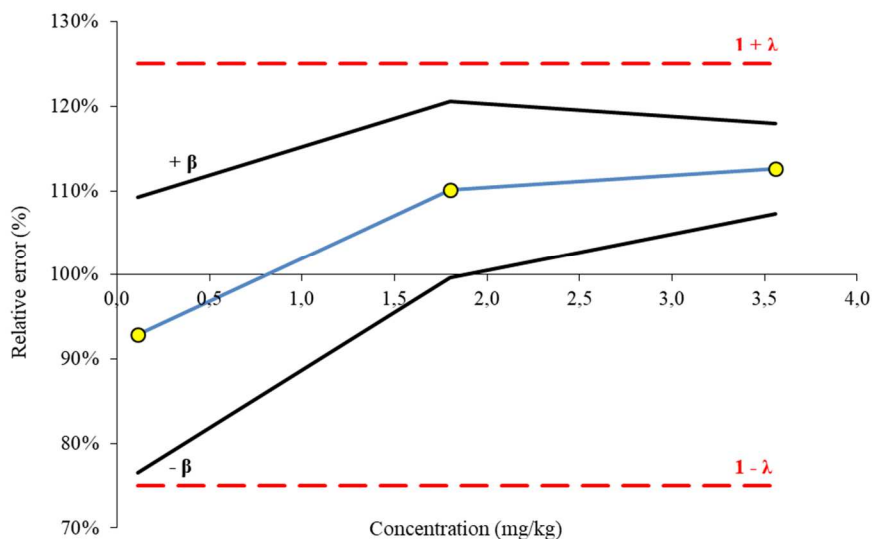
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251 **3. Results and discussion**

252 **3.1 Method validation**

253 The method employed in this study for the simultaneous quantification of Hg_T and Se_T in fish
254 samples is based on a previously published study dealing with multi-elemental determination in
255 food matrices (Chevallier et al. 2015). The sample preparation consisted of microwave (acidic)
256 assisted digestion as described briefly in the section 2.5.1. The validation of the method was carried
257 out using the accuracy profile approach based on the French standard NF V03-110: 2010 (NF V03-
258 110 2010). Briefly, the accuracy profile combines the systematic (trueness) and the random error

259 (repeatability and/or intermediate precision) for a series of analytes' levels in various matrices
 260 within a range of concentrations called the validity domain (Ghosn et al. 2020; Mermet et al. 2012).
 261 To construct the accuracy profile, the accuracy was assessed for each analyte (Se_T and Hg_T) at 3
 262 different levels corresponding to three CRMs, as follows: ERM®-CE101 (trout muscle), NRC
 263 DORM-4 (fish proteins) and the NMIJ CRM 7402-a (codfish tissue), comprising, respectively, a
 264 low level, an intermediate level and a high level of the target elements. A series of five
 265 measurement were carried out in duplicate on (five) different days over a timespan of three months.
 266 For each validation series, an (external) calibration was carried out also in duplicate at seven levels
 267 (0, 1.0, 2.0, 5.0, 7.5, 10 and 20 $\mu g/L$).
 268 In this study, the probability β was set at 80% for Se_T and at 70% for Hg_T , which means that the risk
 269 of expected results falling outside these limits is <20% and <30%, respectively. The acceptance
 270 limits (λ) were set to $\pm 25\%$ for Se_T and to $\pm 35\%$ for Hg_T . The accuracy profiles obtained for Se_T
 271 and Hg_T determination in fishery products by ICP-MS are provided in Figs. 2 and 3.



272 **Fig. 2.** Accuracy profile for Se_T determination in fish by ICP-MS following (closed) microwave acid
 273 digestion ($\beta = 80\%$; $\lambda = 25\%$). Upper acceptance limit: $1+\lambda$; lower acceptance limit: $1-\lambda$; upper acceptance
 274 limit: $+\beta$ and lower acceptance limit: $-\beta$.
 275
 276

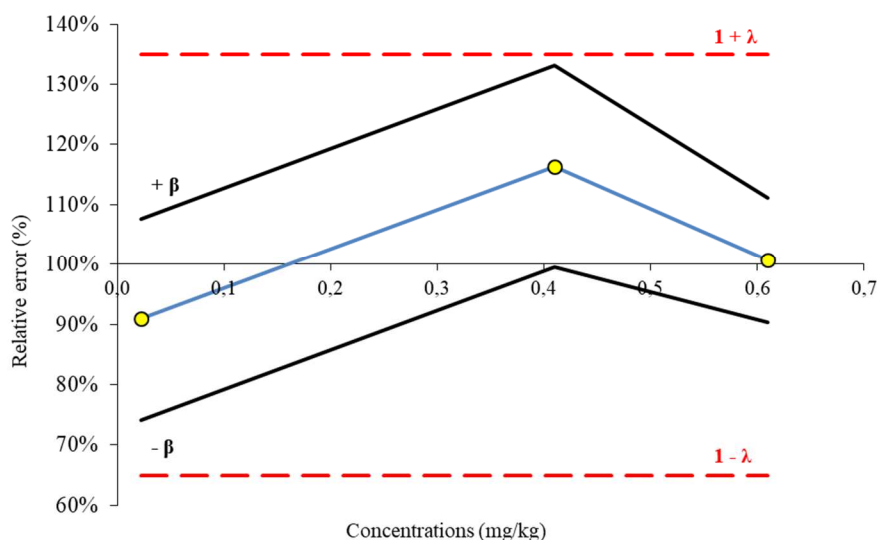


Fig. 3. Accuracy profile for Hg_T determination in fish by ICP-MS following (closed) microwave acid digestion ($\beta = 70\%$; $\lambda = 35\%$). Upper acceptance limit: $1+\lambda$; lower acceptance limit: $1-\lambda$; upper acceptance limit: $+\beta$ and lower acceptance limit: $-\beta$.

As can be seen, β values are comprised within the acceptability limits for the three levels for which the method validation was carried out; this corresponds to a validity domain comprised between 0.11 and 3.56 mg/kg for Se_T and 0.022 and 0.61 mg/kg for Hg_T (ww in all cases).

The bias ranged from 1.0% to 16% for Hg_T and between 7.0% and 13% for Se_T .

The repeatability (expressed as the coefficient of variation, CV_r), varied from 3.3% (highest level) to 6.0% (lowest level) for Se_T and between 1.4% to 6.5% (highest level) for Hg_T determination. The intermediate reproducibility (CV_R) was comprised between 8.6% (highest level) and 14.4% (lowest level) for Hg_T and between 3.3% and 11.0% for Se_T determination.

The limits of detection (LOD) and quantification (LOQ) were determined by the analysis of 21 analytical blanks. The LOQ was calculated as $10 \times$ standard deviation of the blank's levels ($n = 21$) and the LOD as $3/10 \times LOQ$. LOQ of 0.050 mg/kg for Se_T and 0.019 mg/kg for Hg_T determination, respectively, were obtained, while the LOD were 0.015 mg/kg for Se_T and 0.0057 mg/kg for Hg_T . The method accuracy at the LOQ levels was also assessed in this study. For this purpose, ten solutions spiked with Se_T and Hg_T at the LOQs levels were analysed and in all the cases the method accuracy at such low levels was confirmed.

298 **3.2. Exposure study**

299 In this study, physiological status parameters, as the weight and the length of the fish before the
300 exposure study and at the moment of the sampling, were determined. The muscle biomass was
301 estimated based on the weight of the whole fish, assuming that 66% of its weight consists of muscle
302 (Sele et al. 2018). As it was already mentioned, the feed intake was set at 1.5% of the body weight.
303 Using this feed intake, no mortality at all was encountered during this exposure study.

304 It is worth to note that the choice of Se and/or Hg species to be used for the fish exposure studies is
305 still a matter of debate (Ralston et al. 2009). Several studies used inorganic Hg and Se forms, which
306 may not accurately reflect the natural conditions (Ralston et al. 2007).

307 In our study, MeHg and SeMet species were chosen for the exposure study to reflect the real-life
308 conditions. Due the fact that rainbow trout is a carnivore fish, and the fish bioaccumulate Hg in the
309 form of MeHg (Dang et al. 2011; Wang et al. 2019), whereas the predominant Se form in marine
310 animals is present as selenoproteins, including SeMet (Pedrero et al. 2009; Dang et al. 2011; Misra
311 et al. 2012), we chose to expose the fish to SeMet and MeHg during our exposure study. Therefore,
312 enriching the (in house) diet used for the exposure study with these species mimics the chemical
313 forms present in the natural prey, thus, the natural fish diet (Dang et al 2011; Misra et al. 2012).

314 In this study, Se_T and Hg_T levels solely were determined; indeed, speciation analysis of MeHg and
315 SeMet (and other Se species) in the fish muscle could have provided more comprehensive data
316 regarding the distribution of Hg and Se species in fish upon exposure. Nevertheless, it is known that
317 the predominant species in fish muscle are SeMet and MeHg and when the fish diet is supplemented
318 with organic species (e. g. MeHg and SeMet), Se_T and Hg_T are highly correlated with the levels of
319 SeMet and MeHg, respectively (Sele, et al. 2018; Dang et al 2011; Misra et al. 2012).

320 The results in terms of Hg_T and Se_T levels in diets, in muscle and the BF_s of Hg and Se from the
321 diet to the muscle of the Rainbow trout are reported in the Table 3.

Table 3. Hg_T and Se_T levels in diets (mg/kg ww, mean ± SD, n = 3) and muscle tissue (mg/kg ww, mean ± SD, n = 5), as well as the bioaccumulation factors (BF, %) from the diet in the muscle tissue of rainbow trout.

Sample	Mass fraction (mg/kg ww)		BF (%)	
	Hg	Se	Hg	Se
Diet	0.241 ± 0.049	5.41 ± 1.62		
Muscle at t ₀	0.027 ± 0.002	0.14 ± 0.013	368	99
Muscle at t ₃	0.140 ± 0.008	0.91 ± 0.117		

322

323 As can be seen from Table 3, excellent bioaccumulation of MeHg (368%) and SeMet (\cong 100%)
324 took place from the in-house made diets to the muscle of the rainbow trout exposed to these species
325 through the diets. This confirms, in the time tested in our study, that for fish, MeHg and SeMet are
326 highly bioavailable species of Hg and Se, respectively.

327 It is also worth to note that the steady state between absorption and elimination of the SeMet was
328 achieved. For Hg, the bioaccumulation of MeHg from the diet to the muscle after 3 months of
329 exposure is still predominant ($>100\%$), hence explaining the bioavailability of this species
330 (Gochfeld et al. 2021). The high bioaccumulation of MeHg in the muscle could also result from the
331 low elimination rate of this element (Larsen et al. 1995).

332 Hg_T levels in the fish muscle tissue after exposure in different conditions are reported in Table 4.

Table 4. Hg_T levels in rainbow trout muscle tissue (mean \pm SD, n = 5) exposed to SeMet and MeHg via an in-house prepared diet, in various conditions during one (t₁), two (t₂) and three (t₃) months, respectively (also compared to the controlled conditions, t₀).

Exposure group	Hg _T mass fraction (mg/kg ww)				RSD (%) ^a		
	t ₀	t ₁	t ₂	t ₃	t ₁	t ₂	t ₃
G0: Control		0.029 ± 0.002	0.031 ± 0.002	0.034 ± 0.003	6.9	6.5	8.8
G1: SeMet		0.033 ± 0.003	0.031 ± 0.002	0.030 ± 0.003	9.1	6.5	10.0
G2: MeHg	0.027 ± 0.002	0.074 ± 0.006	0.107 ± 0.008	0.140 ± 0.008	8.1	7.5	8.1
G3: SeMet and MeHg		0.064 ± 0.005	0.127 ± 0.013	0.135 ± 0.006	7.8	10.2	5.7
G4: SeMet (one month) then MeHg (2 months)		0.030 ± 0.003	0.073 ± 0.004	0.103 ± 0.008	10.0	5.5	7.8
G5: MeHg (one month) then SeMet (2 months)		0.064 ± 0.002	0.068 ± 0.004	0.056 ± 0.001	3.1	5.9	1.8

^a relative standard deviation (%) for the analysis of 5 fish individually.

333

334 Excellent precision (RSD $\leq 10\%$, see Table 4) was obtained in terms of MeHg bioaccumulation by
335 the five fish individuals exposed to this contaminant in various conditions. The precision in SeMet
336 accumulation is lower, especially when the fish were exposed to SeMet individually, when the RSD
337 was $\cong 15\%$ (see Table 5).

As can be seen from Table 4, Hg_T level in the control group (G0) and in the fish supplemented with SeMet solely (G1) remained constant throughout the study (also compatible with the control group). This suggests that vestigial Hg in the diet did not contribute to any Hg bioaccumulation in the muscle and hence the results obtained in this study are related solely to the enriched diet (with SeMet and MeHg). On the other hand, Hg_T levels in the muscle of the exposed to MeHg solely (G2) increased 2.7 (t₁), 4 (t₂) and 5 (t₃) fold, respectively, compared to the control group (G0), which shows a quasi linear bioaccumulation ($R^2 \cong 0.99$) during the whole period of the exposure. Similarly, the levels of Se_T in the fish (muscle tissue) after exposure in the same conditions (G0-G5) are reported in Table 5.

Table 5. Se_T levels in muscle tissue (mean \pm SD, n = 5) of rainbow trout exposed to SeMet and MeHg via an in-house prepared diet, in various conditions during one (t₁), two (t₂) and three (t₃) months, respectively (also compared to the controlled conditions, t₀).

Exposure group	Se _T mass fraction (mg/kg ww)				RSD (%) ^a		
	t ₀	t ₁	t ₂	t ₃	t ₁	t ₂	t ₃
G0: Control		0.151 \pm 0.012	0.152 \pm 0.018	0.158 \pm 0.013	7.9	11.8	8.2
G1: SeMet		0.523 \pm 0.072	0.867 \pm 0.132	0.910 \pm 0.117	13.8	15.2	12.9
G2: MeHg	0.141 \pm 0.013	0.162 \pm 0.007	0.166 \pm 0.007	0.168 \pm 0.014	4.3	4.2	8.3
G3: SeMet and MeHg		0.537 \pm 0.040	0.921 \pm 0.034	1.115 \pm 0.088	7.4	3.7	7.9
G4: SeMet (one month) then MeHg (2 months)		0.526 \pm 0.029	0.529 \pm 0.016	0.436 \pm 0.015	5.5	3.0	3.4
G5: MeHg (one month) then SeMet (2 months)		0.149 \pm 0.004	0.557 \pm 0.023	0.783 \pm 0.079	2.7	4.1	10.1

^a relative standard deviation (%) for the analysis of 5 fish individually.

The levels of Se_T in the control group (G0) did not differ significantly during the whole experiment; the relative standard deviation of the values corresponding to t₀, t₁, t₂ and t₃ was $\cong 5\%$ and $p = 0.33$. This indicates also that vestigial Se in the diet did not contribute to any Se bioaccumulation from diet to fish when fish were not supplemented with the Se rich diet. However, unlike the G0, where Se_T levels maintained constant in the absence of Se supplementation, in fish with the same Se exposure conditions, but with MeHg dietary exposure (G2), a slight increase in Se_T levels was observed ($p = 0.004$).

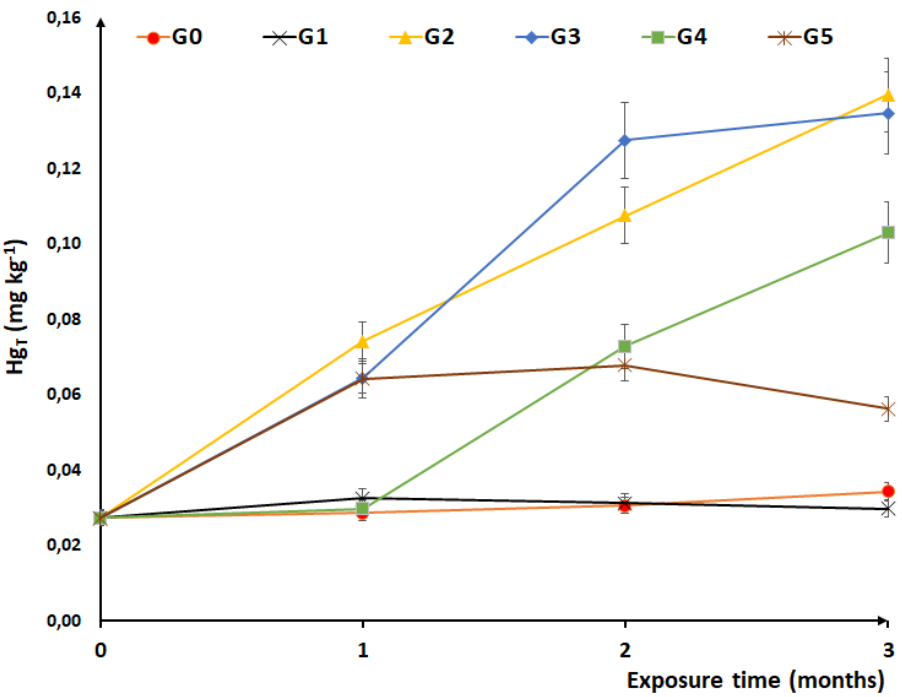
357 When the fish were supplemented with SeMet enriched diet (G1), the Se_T content in the muscle was
358 3.7 (t₁), 6 (t₂) and 6.5 (t₃) higher compared to the control group. It is interesting to note that the
359 increase of the Se_T level up to 2 months was linear ($R^2 = 0.99$) while at t₂ a saturation occurred (no
360 statistical difference between Se_T levels at t₂ and t₃). Thus, following 90 days of dietary SeMet
361 exposure, Se_T muscle burden increased significantly, but the values reached were still lower than the
362 toxic effect threshold of Se in fish (1.0 µg/g ww).

363 It is worth to note that the Se antagonistic effects on Hg can be seen on two different sides. On one
364 side, one can consider the reduced MeHg bioaccumulation by fish in the presence of (relatively)
365 high levels of Se species (SeMet in our study). On the other side, the detoxification of fish (related
366 to its MeHg content) when it is exposed to SeMet can also be considered. In our study we took into
367 consideration both sides, by studying the simultaneous co-exposure of fish to MeHg and SeMet
368 (G3) but also sequentially (G4 and G5, respectively).

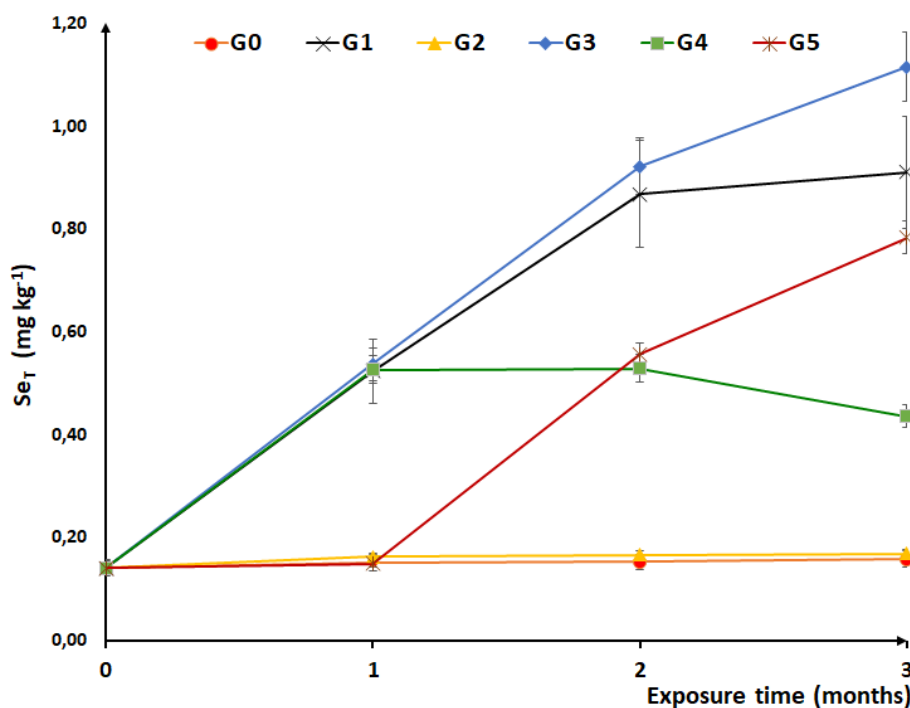
369 When the fish were exposed to SeMet and MeHg simultaneously (G3), significant MeHg uptake
370 occurred only up to t₂ (see also Fig. 4a), while Se_T increased steadily for the whole exposure study
371 ($R^2 \cong 0.98$). Additionally, a slightly higher bioaccumulation of SeMet was noticed when the fish
372 was supplemented with MeHg and SeMet in the same time than when it was supplemented alone
373 (G1). When the fish were supplemented with MeHg and SeMet simultaneously (G3), MeHg level is
374 similar ($p = 0.31$) to that obtained by supplementation with MeHg solely (G2, t₃), while at short
375 exposure time (t₁), a lower accumulation of MeHg (-14%) was observed (see Table 4).

376 The bioaccumulation of SeMet and MeHg does not present the same behaviour in fish exposed to
377 both species in comparison to the ones exposed individually to SeMet and MeHg. An increase in
378 the Hg_T and/or Se_T levels from t₀ to t₃ is observed when they are present in the diet, in all tested
379 conditions, hence confirming that these elements are bio-accumulated along the 3 months of the
380 experiment.

381 It is interesting to note that in the case of G3, a saturation of the MeHg bioaccumulation appeared at
 382 t_2 (see Fig. 4a). ANOVA was performed to compare the Hg_T levels at t_2 and t_3 , which confirmed
 383 that they were not statistically different ($p = 0.30$).
 384 To assess the Hg-Se antagonism in fish, a group of rainbow trout was preliminarily exposed to
 385 SeMet during one month and then to MeHg during the following two months (G4). As can be seen
 386 from Table 4 and Fig. 4a, at t_3 , the fish bioaccumulates less MeHg when exposed firstly to SeMet (1
 387 month, G4) compared to the exposure to MeHg solely (G2). However, this is not necessarily due to
 388 the inhibitory effect of SeMet but most likely due to the lower duration of exposure to MeHg (two
 389 months only). Actually, MeHg bioaccumulation at t_3 in G4 (two months exposure) is comparable (p
 390 $= 0.41$) with that of t_2 in G2 (2 months exposure in both cases).
 391 As can also be seen from Table 5 and Fig. 4b (G4), SeMet level remains constant ($p = 0.87$) one
 392 month after ending the supplementation (see t_1 and t_2) but it declines ($\cong -18\%$) two months after the
 393 supplementation is stopped (see t_3).



(a)



(b)

Fig. 4a-b. Variation of Hg_T (a) and Se_T (b) levels in the muscle of rainbow trout during different scenarios of exposure to SeMet and MeHg in a dynamic system via an in-house prepared diet. G0: control group, G1: group exposed to SeMet enriched diet, G2: group exposed to MeHg enriched diet, G3: group exposed simultaneously to SeMet and MeHg; G4: group exposed initially to SeMet (one month) and then to MeHg (two months) and G5: group exposed initially to MeHg (one month) and then to SeMet (two months).

To assess the detoxification role of SeMet towards MeHg in fish, a group of rainbow trout was initially exposed to MeHg (1 month) and then to SeMet via the corresponding enriched in-house prepared diets (G5). When comparing the bioaccumulation of MeHg observed in the first month of exposure in this group (G5, t_1), to the fish also exposed to MeHg for the same period but with simultaneous exposure to SeMet, (G3, t_1), it was observed that MeHg was bioaccumulated similarly ($p = 0.95$). That means that the presence of SeMet did not influence the bioaccumulation of MeHg. Additionally, it was observed that MeHg level remained constant ($p = 0.14$) one month after the substitution of MeHg with SeMet (G5, t_2). However, a slight decrease ($\cong -18\%$) in MeHg level was noticed after two months of fish exposure to SeMet and no MeHg (G5, t_3). We can relate this observation to a detoxification effect of the fish in terms of MeHg as a result of its supplementation with SeMet enriched diet, which is also in agreement with other studies (Amlund et al. 2015; Bjerregaard et al. 2011). On the other hand, we could associate the observed decrease in MeHg concentration to a natural detoxification due to the fact that MeHg exposure was stopped. However,

417 this hypothesis it is not likely because when comparing the MeHg bioaccumulation behaviour
 418 observed in the control group (non MeHg enriched diet), the levels of MeHg in the fish remained
 419 constant throughout the exposure experiment suggesting that no natural detoxification occurs in this
 420 case.

421 However, as observed by several authors (Ralston et al. 2009; Huang et al. 2013; Khan et al. 2009),
 422 the overall net protective effect of Se over Hg toxicity will depend on the relative concentrations of
 423 Hg and Se, justifying the importance of evaluating also the Se/Hg molar ratio. Se and Hg molar
 424 ratios in the diets and the fish muscle are shown in Table 6.

Table 6. Se and Hg molar ratio in the different types of diet as well as in the muscle tissue of rainbow trout exposed to MeHg and SeMet in different conditions.

Diet	n _{Se} / n _{Hg} ^a	Exposure group	n _{Se} / n _{Hg} ^a			
			t ₀	t ₁	t ₂	t ₃
Control	44	G0: Control	13	13	12	12
MeHg enriched	9	G1: SeMet		40	71	77
SeMet enriched	274	G2: MeHg		6	4	3
MeHg + SeMet enriched	55	G3: SeMet and MeHg		21	18	21
		G4: SeMet (one month) then MeHg (2 months)		45	18	11
		G5: MeHg (one month) then SeMet (2 months)		6	21	36

^a n: number of moles

425

426 The Se/Hg molar ratio is always considerably >1, suggesting that Se is always in excess relative to
 427 Hg, both in the fish muscle and the diet (including in the diet control fish and diet, respectively).
 428 Therefore, for fish, n_{Se} / n_{Hg} >1 assures both the normal Se metabolism and the MeHg detoxification
 429 (Ralston et al. 2009).

430 As expected, the lowest Se/Hg molar ratios are observed in G2 (exposure to MeHg solely), while
 431 the highest Se/Hg molar ratios are measured in the fish from G1 (exposure to SeMet solely).
 432 Deserves mention that some authors reported that the benefit of Se supplementation in prevention of
 433 MeHg accumulation is dependent on the chronology of the exposure treatments, being only
 434 observable when Hg and Se are provided simultaneously (Naganuma et al. 1983). Lower mortality
 435 rate was observed in fish pre-treated with SeO₂ before HgCl₂ administration in comparison to those
 436 exposed to HgCl₂ treatment only (Cuvin et al. 1988). Nagamuna et al. (1983) reported that a

437 delayed administration of Na_2SeO_3 had no protective effect in mice, while Agarwal et al. (2007)
438 observed even a greater accumulation of Hg in mice undergoing a post-treatment with Na_2SeO_3
439 (Naganuma et al. 1983; 387 Agarwal et al. 2007). To respond to this controversy, as it was already
440 presented above, we carried out an exposure experiment by supplementing the fish firstly with
441 MeHg (one month) and then with SeMet during two months (G5). Our results show that when the
442 supplementation with SeMet starts one month after the exposure to MeHg, the Se/Hg molar ratio
443 (t_2) is comparable with that at t_2 in case of simultaneous exposure (G3). The data also show that
444 bioaccumulation of equimolar Se and Hg levels in the fish muscle does not occur in any of the
445 conditions of our study (using diet with or without supplementation with SeMet and/or MeHg
446 species). Finally, no correlation can be established between the molar ratio in the diet and the fish
447 muscle in any of the exposure condition.

448

449 **Conclusions**

450 This study focused on the dietary exposure of a river water fish species (rainbow trout) to MeHg
451 and/or SeMet via an in-house prepared diet supplemented with these Hg and Se species. The study
452 was carried out in dynamic conditions by using various scenarios, relying on exposure to MeHg and
453 SeMet individually, simultaneously but also sequentially. For the simultaneous determination of the
454 levels of total Hg and Se in fish muscle, a novel method based on ICP-MS was validated using the
455 accuracy profile. Excellent precision and accuracy were obtained, hence making it fully applicable
456 to the trace and ultra-trace determination of total Hg and Se in fish undergoing exposure to SeMet
457 and MeHg.

458 Our results show a quasilinear bioaccumulation of MeHg in the fish muscle during three months
459 when they are exposed individually to this species, while saturation occurs for SeMet after two
460 months of exposure. Also, a threshold in total Hg level is reached when the fish are exposed
461 simultaneously to MeHg and SeMet. It is also interesting to note a decrease of MeHg burden was
462 observed when the fish were exposed to SeMet after being first exposed to MeHg, hence indicating

463 the MeHg detoxification due to SeMet supplementation. This in-vivo exposure study confirms the
464 previous reports regarding the possible antagonistic effect of Se and Hg in fish.
465 The study must be a pursuit with the speciation analysis of Hg (MeHg and its inorganic precursor,
466 Hg²⁺) and Se (SeMet and other species such as inorganic Se(IV)/Se(VI) and selenocysteine/SeCys)
467 to decipher the mechanism of the in-vivo interaction between Se and Hg in fish and the protective
468 effect of Se towards Hg contamination. It could also be extended to carrying out the exposure
469 during a longer duration (>3 months) using other fish species and also using Hg²⁺ and other Se
470 species (e.g. SeCys, Se(IV), Se(VI)) to deeply understand the Hg-Se antagonism in fish.

471

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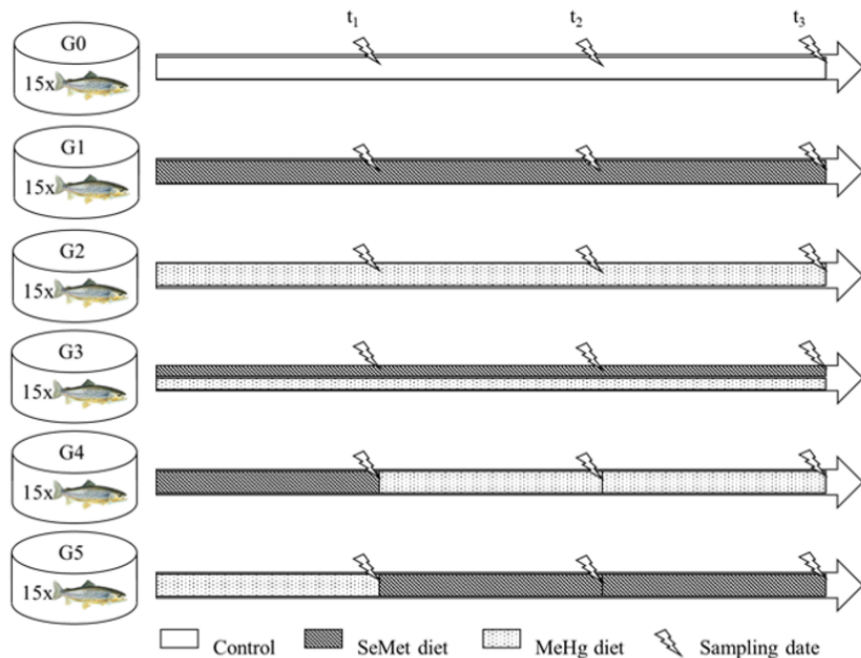
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586

587

Exposure study



Se and Hg Quantification



Antagonistic effect of Se and Hg in fish

