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Drinking water consumption and association between actual and perceived risks of endocrine disrupting compounds

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Drinking water contains emerging contaminants, i.e., endocrine disrupting compounds (EDCs). However, the extent to which it is publicly viewed as a potential risk that requires attention (public awareness, political obligation, and regulatory efforts) is substantially underrated. Thus, this study investigated drinking water consumption patterns among consumers of different life stages, evaluated household practices using tap water as daily drinking water, and examined the actual risk as well as consumers' perception of tap water quality for drinking with the potential EDCs contamination. Collectively, the present study is of great concern for regional database profiling and supporting human health risk assessment in regulating contamination and exposure of EDCs. It also provides an empirical and theoretical contribution to current public risk perception of EDCs in tap water, and promoted the formulation of risk communication and governance strategies for the development of risk behaviors in adopting public participation in the drinking water supply system monitoring and management framework.

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INTRODUCTION

The principal chemical constituent of the human body, water controls biochemical reactions within cells, acts as a material transport medium, and maintains adequate blood volumes[1]. Water is also influential in human health, comfort, and performance, as body water regulates human thermal environments (human thermoregulation), thereby controlling physiological and psychological responses[2]. Dehydration of body mass (≥2%) can cause impaired thermoregulatory function and elevated cardiovascular strain, also taking time to accumulate[3]. Thus, drinking enough water is essential to restore the large quantity of water lost daily.

While drinking water is mandatory to maintain life for survival, there is little consensus on safe drinking water access for consumption. Over the past few decades, the concerns about quality of drinking water supply were limited to (i) microbial contamination, (ii) aesthetic problems, and (iii) chemical contents[4–8]. The chemical contaminants were mostly disinfectants, disinfection by-products, nutrients, metals, and major ions. Water contamination and the subsequent health issues were due to both natural processes and anthropogenic activities originating primarily from the industrial revolution[9]. To date, threats to the global drinking water supply system (i.e., water source pollution, incomplete removal, and water supply insecurity) and insufficient regulatory frameworks have prompted human exposure to emerging organic pollutants, especially endocrine disrupting compounds (EDCs) via daily consumption of drinking water, especially tap water. Trace concentrations of EDCs such as pharmaceuticals, drugs, personal care products, hormones, plasticizers, and pesticides were detected in global drinking water[10]. The broad scopes of EDCs are reviewed for having endocrine disrupting effects through a variety of modes of action and mechanisms, thus causing health effects in exposed individuals and populations in the form of acute and chronic diseases.

EDCs are released from point and non-point sources. Many hydrophilic and persistent EDCs are able to penetrate through water utility systems that were designed to remove only traditional pollutants and contamination is released, even with advanced treatment technology, due to the various physicochemical properties, transport pathways, and fates of the EDCs[10]. Thus, the presence of EDCs in the drinking water supply (tap water) was mainly due to the inadequate remediation technologies in drinking water treatment plants, other than the influences of land use on the pollution in the drinking water sources (surface water). Meanwhile, variation in treatment efficiency of EDCs is potentially impacted by their corresponding pollution levels in raw water[11]. Further, the dynamics and partitioning of EDCs in the distribution network depend upon varying design and operation of the system[12].

Alternatively, the use of additional household water utility systems (e.g., filtration and purification devices) at home or other point of use is commonly practiced, especially in developing countries whose drinking water is of uncertain quality. To date, membrane processes such as reverse osmosis and nanofiltration have been promoted as more capable of remediating EDCs[13]. Further, water purification requires membranes with improved selectivity relative to permeability[14]. Replacing conventional polymers with emerging materials, ultrafast molecular separation membranes are highly selective towards emerging organic pollutants[15]. However, water purifiers have recently been highlighted as a source of contamination of EDCs in drinking water, particularly of organophosphate flame retardants[16]. Consequently, the concerns about removal efficiency, cost effectiveness, and sustainable use remain while households are trying to reduce the risk of contaminants exposure and waterborne disease arising from contamination during water supply distribution and storage.

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Risk assessment of contaminants is part of the scientific effort facilitating the multibarrier approach in drinking water supply system monitoring and management for safe access to water[17]. The guidelines and database in the US EPA "Exposure Factors Handbook" have been commonly used in assessing exposure to environmental chemicals and the human health risk associated[11,18,19]. Historically, default values of body weight and daily water intake for adults (≥10 years of age) (70 kg; 2 L/day) and children (<10 years of age) (10 kg; 1 L/day) were assumed[20]. In order to reduce uncertainty in the exposure assessment and provide a more conservative worst-case scenario, human health life-stage risks incorporating different age-specific exposure where body weight and daily water intake were explicitly distinguished into relevant life stages[19]. However, humans' growth rates are different in different countries[21]. Intake of drinking water varies in different regions and countries, resulting from seasonal and climate variation[19,22].

Inadequate monitoring and management of water resources are expected due to the lack of public awareness and political obligation in promoting preventive actions and interventions to ensure safe drinking water. The inconsistent and skewed association between perceived and actual quality of drinking water was observed in terms of organoleptic properties, health risk, and practice[7]. Willingness to pay for safe access to drinking water with enhanced quality and infrastructure depended greatly on consumers' risk perception, as individual perception of risk is crucial in the development of risk behavior[23]. Risk is the product of the likelihood of occurrence and potential consequences of a hazard. Meanwhile, risk perception varies depending upon the type of risk, risk context, personality of the individual, and social context[24]. Despite the fact that the water was supplied from the same water system, the opinions of communities on the water's quality were varied. Currently, risk perception of EDCs in drinking water and its role in adopting risk prevention and intervention are unknown. This highlights the need for bridging the gap in the risk perception and the formulation of strategies (goals, methods, and materials) for effective risk communication and governance[25].

Thus, this study aims to (i) investigate consumption patterns among different life stages of consumers, (ii) evaluate household practices concerning the use of tap water as daily drinking water, and (iii) examine the actual risk and consumers' perception about using tap water with potential EDCs contamination for drinking. The results are expected to be useful to current knowledge of public risk perception of EDCs in tap water, where the subsequent formulation of risk communication and governance strategies are relevant for development of risk behaviors, and alerting about the need for public involvement in a multi-barrier approach in the monitoring and management framework of the drinking water supply system.

RESULTS AND DISCUSSION

Sociodemographic of respondents

A total of 140 households completed surveys with a response rate of 45.0%. The respondents were comprised of 48.6% males ($n = 68$) and 51.4% females ($n = 72$) in the general population aged 18 to 64 years, which were differentiated into five age groups: ≤19 (1.4%); 20–29 (22.1%); 30–50 (67.1%); 51–59 (5.0%); ≥60 (4.3%). There was a variation in terms of education levels and employment status; the majority of respondents were Bachelor-degree holders (at least 45%) and working as government servants (60.0%), as tabulated in Table 1. The accounted median monthly household income of Putrajaya is RM 7512 (~USD 1803, mean monthly household income of RM 10401, ~USD 2496), exceeding the national level (RM 4585, ~USD 1100)[26]. The survey covered household groups: bottom 40% (B40), middle 40% (M40), and top 20% (T20), classified into income groups ≤RM 2999, RM 3000–4999, RM 5000–6999, RM 7000–8999, RM 9000–10999, RM 11000–12999, and ≥RM 13000, where RM 1 approximately equivalent to USD 0.24 in average. On an average, respondents had lived in Putrajaya for seven years.

Human morphology and drinking water consumption patterns

The present study involved 140 households with 257 total respondents ($n = 257$), consisting of infants ($n = 4$, aged less than 1 year; birth–5; 6–11 months), children ($n = 77$, aged 1 to 9 years; 1–3; 4–6; 7–9 years), adolescents ($n = 37$, aged 10 to 19 years; 10–14; 15–19 years), adults ($n = 133$, aged 20 to 59 years; 20–29; 30–50; 51–59 years) and elderly ($n = 6$, aged more than 60 years) (Table 2). Age groups were categorized based on previous studies[27–30].

There were no significant differences between males ($n = 125$) and females ($n = 132$) in terms of body weight ($t(235) = 1.671$, $p = 0.096$), body height ($t(225) = 0.804$, $p = 0.422$), body mass index ($t(246) = 1.116$, $p = 0.266$), and daily water intake ($t(255) = 0.483$, $p = 0.629$). Surprisingly, males consumed more water than females in the United States and Australia[19,31]. Body weight showed a significant positive correlation to height based on Pearson product-moment correlation test ($r = 0.861$, $p < 0.001$). Moreover, daily water intake was observed positively correlated to body weight ($r = 0.376$, $p < 0.001$) and height ($r = 0.347$, $p < 0.001$), indicating the potential influence of human morphology and growth in daily water consumption. Table 2 depicts the mean body weight, body height, body mass index, daily water intake, and daily water intake per body weight of the respective age group in the present study. Age groups had a significant difference in term of body weight, body height, body mass index, and daily water intake (one-way analysis of variance, $p < 0.001$). Malaysian frequency of exposure to pollutants in tap water was 1 (365 days/365 days, 95th-percentile value).

Drinking water ingestion pattern varied between life stages (Fig. 1). The difference was due to the changes in human behavioral and physiological characteristics (development and age-specific) under varying environmental conditions[19]. The early life stage (infants and children) had greater drinking water ingestion on a body weight basis compared to adolescence and adulthood. Further, Fig. 1 depicts the comparison of daily water intake per body weight in the present study to US EPA[19] guidelines for exposure assessment. American adolescents consumed drinking water at the lowest rate; meanwhile, the present study reported the elderly (≥60 years of age) to have the lowest water intake rate. Both studies revealed the constant daily drinking water intake per body weight throughout adulthood. The lower daily water intake rate of elderly Malaysians was related to the younger retirement age and thus the lower energy consumption and water restoration. Thus, the application of regional data for exposure and health risk assessment may be less relevant in some regions because of the variation in contamination, human growth, and drinking water intake across the world. The limitation of not having detailed particulars on drinking water intake and body weight of the local population was highlighted in a previous study[18]. Therefore, data collection and analysis on the local human morphology, drinking water consumption patterns, and household practices regarding tap water as drinking water were done to better reflect local exposures to EDCs.

Household practices on tap water as drinking water

A majority of households (52.9%) were observed taking both bottled and tap water as their daily drinking water sources. The remainder chose either only tap water (35.7%) or bottled water (11.4%). A high percentage of households (87.1%, $n = 122$) practice tap water treatment before daily consumption as drinking water (Fig. 2a). Other households ($n = 18$) do not treat water as

Table 1. Descriptive statistics about risk perception of drinking water supply security with potential EDC contamination.

Demographic characteristic	Percentage (%)	Mean risk perception (SD)[a]	Difference	Significance level
Gender*				
Male	48.6	2.49 (0.66)	$t(555) = 2.321$, $p = 0.021$	$p < 0.05$
Female	51.4	2.35 (0.75)		
Age groups (years)				
≤19	1.4	2.13 (0.64)	$F(4, 555) = 1.363$, $p = 0.246$	$p > 0.05$
20–29	22.1	2.40 (0.76)		
30–50	67.1	2.42 (0.72)		
51–59	5.0	2.39 (0.50)		
≥60	4.3	2.71 (0.46)		
Education level				
Secondary education	8.6	2.56 (0.62)	$F(4, 555) = 1.332$, $p = 0.257$	$p > 0.05$
Diploma	25.0	2.36 (0.70)		
Bachelor	45.0	2.40 (0.74)		
Masters	19.3	2.47 (0.70)		
Doctorate	2.1	2.67 (0.65)		
Employment status				
Government	60.0	2.42 (0.71)	$F(6, 553) = 0.703$, $p = 0.647$	$p > 0.05$
Private	14.3	2.45 (0.73)		
Housework	3.6	2.45 (0.76)		
Retired	5.0	2.61 (0.50)		
Self-employed	5.7	2.47 (0.62)		
Student	9.3	2.29 (0.80)		
Others	2.1	2.33 (0.89)		
Income groups (RM)				
≤2999	23.6	2.39 (0.68)	$F(6, 553) = 0.831$, $p = 0.546$	$p > 0.05$
3000–4999	20.7	2.47 (0.69)		
5000–6999	20.7	2.47 (0.70)		
7000–8999	12.1	2.34 (0.82)		
9000–10999	15.0	2.42 (0.70)		
11000–12999	3.6	2.60 (0.60)		
≥13000	4.3	2.25 (0.79)		

SD Standard deviation; [a] Scale with 1 (disagree) to 3 (agree), is aggregate of the "strongly disagree", "disagree", "agree", and "strongly agree" responses, where "3" includes those who responded "strongly agree" or "agree" with the statement; * Significant at the 0.05 level (2-tailed), *p* values calculated through inferential statistics, i.e., independent *t*-test and one-way analysis of variance.

drinking water as most of them (16 out of 18 households) were consuming only bottled water, whereas only two of them had a direct intake of tap water without any treatment. Comparatively, bottled water was primarily chosen among consumers in other countries such as the United States, Australia, Canada, Czech Republic, France, Italy, Korea, Mexico, the Netherlands, Norway, and Sweden[32,33].

There were a higher proportion of males in the profiles of (i) both bottled and tap water (54.4 and 51.4% of males and females, respectively) and (ii) individual tap water (36.8 and 34.7% of males and females, respectively), but not that of individual bottled water (8.8 and 13.9% of males and females, respectively). The least selected option, consumption of bottled water, was only slightly more preferable by females compared to males (5.1% difference). Choice of tap water only was more favorable among houseworkers and retired people who stay at home for longer than those who chose otherwise; thus, it was the elderly (aged ≥60 years) with the highest proportion at 66.7% (the remaining 33.3% preferred tap water mix with bottled water). Up to 83.3% of T20 consumers (household income ≥RM 13000) were prone to drink tap water only (in contrast, the other 16.7% chose bottled water only), whereas B40 and M40 consumers (household income ≤RM 12999) preferred to mix the use of bottled and tap water (47.6–60.0%), followed by tap water only (27.3–47.6%). People with postgraduate qualification (Masters and Doctorate) prioritized the option of tap water only at a proportion of 48.1 and 66.7%, respectively, which was higher than the other education levels (ranged between 22.9–38.1% versus 50.0–68.6% for the combination of bottled and tap water). The association between demographic characteristics and household choices of drinking water was similar to the previous study, except that a higher proportion of males were recorded as choosing bottled water only[5].

Based on the survey, attachment of home purification systems, i.e., point of use (connected directly to the tap) and point of entry (connected where the water enters the house) were common among the households. As shown in Fig. 2a, treatment with a purification device was the most practical treatment method (76.2%). Some households tended to further boil the purified tap water for their daily drinking water consumption (7.4%). Meanwhile, 16.4% responded that boiling was their only treatment practice. A chi-square test found no significant association between demographic characteristics and household choices about drinking water

Table 2. Age groups and respective mean body weight, body height, body mass index, daily water intake, and daily water intake per body weight.

Age group	Body weight (kg)	Body height (m)	Body mass index	Daily water intake (L/day)	Daily water intake per body weight (L/kg/day)
Infants					
Birth-5 months	2.70	0.50	5.4	0.25	0.093
6–11 months	6.37	0.67	10.3	0.57	0.089
Children					
1–3 years	11.17	0.77	14.8	0.96	0.086
4–6 years	15.77	1.03	15.4	1.27	0.081
7–9 years	23.90	1.20	20.2	1.38	0.058
Adolescents					
10–14 years	35.03	1.42	24.5	1.30	0.037
15–19 years	56.83	1.60	35.4	1.63	0.029
Adults					
20–29 years	60.19	1.61	37.2	1.65	0.027
30–50 years	70.54	1.64	43.1	1.94	0.028
51–59 years	72.71	1.56	46.7	2.07	0.028
Elderly					
≥60 years	73.50	1.67	44.0	1.55	0.021

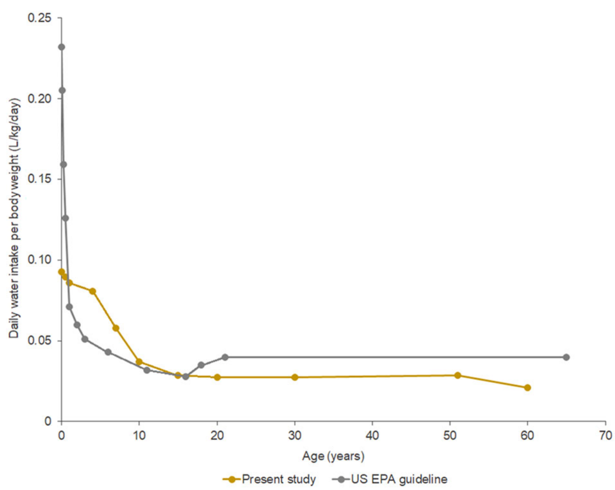

Fig. 1 Comparison of consumers' daily water intake per body weight in the present study to US EPA guideline. Human growth and drinking water intake vary. The variation concerns the relevance of the application of regional data for exposure and health risk assessment. Data from US EPA guidelines are based on ref. [19].

($p > 0.05$); that is, households of different demographic groups made choices about daily drinking water sources and treatment which were independent of their group categorization. Surprisingly, age and gender were the significant variables in choosing bottled water as the source for drinking water[32].

Among the respondents, 67.9% were married ($n = 95$, only 73 of whom had children), followed by those who were never married (31.4%, $n = 44$) or divorced (0.7%, $n = 1$). All parents had the same drinking water sources and practices regarding tap water as for their children's daily water intake. Over half of the parents (52.1%) provided their children with bottled and tap water in combination, followed by tap water (39.7%) or bottled water (8.2%) only. Filtration using a purification device was the most preferred practice (79.1%) before allowing children to drink water, followed by boiling (17.9%) and employment of both filtration and boiling (3.0%), except for those consuming only bottled water with no household treatment (Fig. 2b). Moreover, there was an association between the age group of parents and their practices preparing tap water for their children to drink ($\chi^2(6) = 13.24$, $p = 0.039$). Parents aged 20–29 years choose equally between filtration and boiling method. A higher proportion of respondents in age groups 30–50 and 51–59 (at least 80.0% among them) preferred filtration using a purification device. Nonetheless, up to 33.3% of parents in the age group ≥60 years chose a combination of filtration and boiling, although filtration was the preferred method (66.7% among them).

Households were taking both bottled and tap water at the same time, and resorted to bottled water when they lost trust in tap water quality for drinking[7,32,33]. Also, households were most likely to purchase bottled water and use home purification systems; this is attributed to the households' perception of the better quality, safety, taste, health characteristics, and naturality (mineral water), with affordability, convenience, and social values[7,8,32–35]. However, these perceptions and claims were debatable in terms of the actual quality and long term effects of exposure on a regular basis. For example, the dominant presence of contaminants such as mineral ions (e.g., sodium, potassium, calcium, and magnesium) and EDCs (e.g., plasticizers) in bottled water (mineral and drinking water) with relatively low physicochemical parameters of the drinking bottled water[36,37]. Moreover, the efficiency of purification devices is of great concern when the diverse organophosphate flame retardant contamination and exposure have been attributed to water purifiers[16]. Meanwhile, the households' choice of using tap water as the main daily drinking water source in the present study raises concerns for human exposure to EDCs through daily consumption of drinking water since treatment systems (both treatment plants and home devices) have been proven to be inefficient in removing these emerging contaminants.

Actual risk of EDCs in drinking water

Given that EDCs are present in tap water, a primary choice of drinking water supply among the consumers, humans are potentially exposed to EDCs via drinking water intake. Therefore, regional database profiling is useful to better reflect local exposure and health risk. This involves further incorporating collected data into human health risk assessment with monitoring data, as shown in the following equations. The estimation of

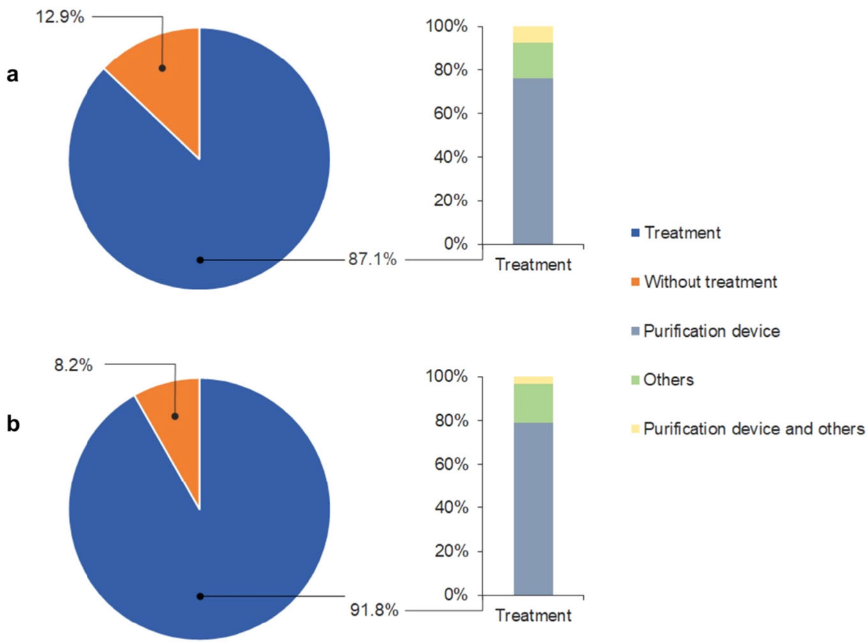

Fig. 2 Household practices for using tap water as drinking water for adults and children. Majority of households purified tap water before daily consumption as drinking water. **a** Adults. **b** Children.

human life-stage health risks with varying local age-specific exposure was able to reduce uncertainty in the exposure assessment and provide a more conservative worst-case scenario. A risk quotient (RQ) value greater than 1 indicates a possible risk of exposure through drinking water.

$$RQ = C_s/DWEL \quad (1)$$

$$DWEL = (ADI \times BW \times HQ)/(DWI \times AB \times FOE) \quad (2)$$

where C_s is the maximum detected concentration (ng/L, to be obtained from monitoring work); DWEL is drinking water equivalent level; ADI is the acceptable daily intake (ng/kg/day); BW is body weight (kg); HQ is the hazard quotient; DWI is the drinking water intake (L/day); AB is the gastrointestinal absorption rate; and FOE is the frequency of exposure (days/365 days)[38,39]. Table 3 shows the exposure factor definitions and values used in human health risk assessment.

Residues were categorized into four groups: (a) residues with all life-stage RQs $> 2.5 \times 10^{-3}$, (b) residues with all life-stage RQs between 2.5×10^{-4} and 2.5×10^{-3}, (c) residues with at least one life-stage RQ between 2.5×10^{-5} and 2.5×10^{-4}, and (d) residues with all life-stage RQs $< 2.5 \times 10^{-5}$. Lifetime RQ profiles from birth to 60 years of age in relation to daily water intake per body weight are depicted in Fig. 3. The estimated RQs of the nine EDC residues via drinking water were $\leq 1.30 \times 10^{-2}$, with the highest at age ≤5 months under dexamethasone exposure. RQs in early life stages, i.e., infants and children (birth to 9 years) were higher than the RQs of adolescents (at least 1.6–3.2 times), adults (at least 2.0–3.4 times), and elderly (at least 2.7–4.4 times), respectively. Among the life stages, infants (birth to 5 months) possessed the highest health risks, whereas the elderly (≥60 years) exhibited the lowest health risks. The potential exposure levels and human health risks were constant throughout adulthood. Human health life-stage RQ profile was highly dependent on the daily water intake per body weight (Fig. 3). RQ of the EDC mixture was estimated based on the summation of individual RQ values of each EDC, accounted highest at 3.28×10^{-2}.

RQ values less than one estimated that there were no potential risks to all the life stages under present exposure to individual and mixture EDCs via drinking water consumption. However, increasing application and unregulated discharges of EDCs based on the (i) inadequate evidence (epidemiological studies) about the risk of human exposure, (ii) underdeveloped risk communication and governance (regulation and public participation), and (iii) unknown risk perception and its role in adopting risk prevention and intervention, will further increase contamination and human exposure[9]. Nevertheless, the present study presented a questionnaire survey in regional database profiling, which is supportive in human health risk assessment of reducing the environmental pollution of EDCs and managing human exposure to them through drinking water ingestion.

Perceived risk of drinking water supply quality

Mean perception of risk, at 2.42 ± 0.71, was between the points "unsure" and "agree" to the issue of present drinking water supply security with the potential of EDC contamination. The public perceived every water quality and health issue as significantly different ($F(3, 556) = 38.844$, $p < 0.001$). Notably, up to 85% of the population was highly concerned about tap water quality (2.81 ± 0.50); however, the concern was less likely attributed specifically to the presence of EDCs (2.57 ± 0.64) ($p = 0.013$). The public was relatively unsure whether tap water was safe to drink (2.02 ± 0.78), as well as the capability of the Malaysia Drinking Water Quality Standard to regulate EDCs in tap water (2.29 ± 0.70). Approximately 39.3% perceived that the Malaysia Drinking Water Quality Standard was capable of regulating EDCs in tap water, although most of the EDCs were not currently regulated under the guideline.

The influence of sociodemographic group on actual or perceived proximity to a potential risk was observed with the affected risk perception of drinking water quality (amplification or attenuation effects)[6,25,40]. Table 1 shows a breakdown of the mean score of public risk perception of drinking water supply security with the potential EDCs contamination and the statistical difference for each of the sociodemographic variables. Overall, a significant difference was observed only in gender, where males (2.49 ± 0.66) perceived a higher risk than females (2.35 ± 0.75) ($t(555) = 2.321$, $p = 0.021$). In this context, males were more confident that Malaysian tap water was safe to drink (2.24 ± 0.74)

Table 3. Exposure factor definitions and values used in human health risk assessment.

Parameter	Unit	Definition	Value	Reference
C_s	ng/L	Maximum detected concentration of EDCs		39
		• Dexamethasone	2.11	
		• Primidone	2.99	
		• Propranolol	0.69	
		• Ciprofloxacin	8.69	
		• Caffeine	5.33	
		• Sulfamethoxazole	0.90	
		• Diclofenac	21.39	
		• Triclosan	9.74	
		• Diazinon	1.80	
ADI	ng/kg/day	Acceptable daily intake		38,51–54
		• Dexamethasone	15	
		• Primidone	700	
		• Propranolol	56000	
		• Ciprofloxacin	7100	
		• Caffeine	150000	
		• Sulfamethoxazole	130000	
		• Diclofenac	1600	
		• Triclosan	12000	
		• Diazinon	90	
BW	kg	Body weight		This study
		• Birth–5 months	2.70	
		• 6–11 months	6.37	
		• 1–3 years	11.17	
		• 4–6 years	15.77	
		• 7–9 years	23.90	
		• 10–14 years	35.03	
		• 15–19 years	56.83	
		• 20–29 years	60.19	
		• 30–50 years	70.54	
		• 51–59 years	72.71	
		• ≥60 years	73.50	
HQ	NA	Hazard quotient	1	38
DWI	L/day	Daily water intake		This study
		• Birth–5 months	0.25	
		• 6–11 months	0.57	
		• 1–3 years	0.96	
		• 4–6 years	1.27	
		• 7–9 years	1.38	
		• 10–14 years	1.30	
		• 15–19 years	1.63	
		• 20–29 years	1.65	
		• 30–50 years	1.94	
		• 51–59 years	2.07	
		• ≥60 years	1.55	
AB	NA	Gastrointestinal absorption rate	1	38
FOE	NA	Frequency of exposure		This study
		• 365 days/365 days	1	

NA Not available.

and the Malaysia Drinking Water Quality Standard was capable of regulating EDCs in tap water (2.44 ± 0.58) than females (1.82 ± 0.78 and 2.14 ± 0.68, respectively). An independent-samples *t*-test showed that the differences between the genders were significant ($t(138) = 3.253$, $p = 0.001$ and $t(138) = 2.822$, $p = 0.005$, respectively).

To illustrate the differences between individuals who had a high or low perception of risk of EDCs in tap water, they were classified into different risk perception communities as follows: low risk perception (i.e., scored ≤2.00 on average; this constituted 27.1% of the respondents) and high risk perception (i.e., scored ≥2.75 on average; this constituted 35.7% of the respondents). Figure 4 depicts a comparison of mean responses of the low- and high-risk perception communities about drinking water supply quality. The low- (1.87 ± 0.74) and high-risk perception communities (2.90 ± 0.30) perceived risk concerning drinking water supply significantly differently at $t(188) = -16.141$, $p < 0.001$.

Most of the males (45.6%) perceived high risk regarding the daily supply of drinking water; meanwhile, there was a higher proportion of low-risk perception females (2.8% higher than the high-risk perception females). Figure 5 shows the proportion of each risk perception community within different groups of demographic characteristics. The high-risk perception community was mostly comprised of the working groups such as government servants, private workers, and self-employed individuals, as well as the retired workers. Similarly, the elderly (aged ≥60 years) had a higher risk perception than the other younger respondents (Fig. 5 and Table 1). Different education levels made up the greater proportion of the high-risk perception community, in which field of study could be an underlying factor. Wealthy people had different risk perception to lower income people; notably, the high-risk perception community had no T20 income group. Also, up to 60% of the M40 income group were in the high-risk perception community. Moreover, the B40 income group had relatively high risk perception (30.3 and 24.2% of high- and low-risk perception groups, respectively). Nonetheless, the chi-square test found no significant influence of demographic characteristics in the distribution of risk perception communities ($p > 0.05$). Beside the sociodemographic factors, the variation in public-perceived risk of EDCs in drinking water was expected due to the different risk processing either based on a rational system (analytical processing system) or a nonrational system (experiential processing system)[9]. Further, future studies on comprehensive conceptualization of the risk processing system and predictors (e.g., cognitive and affective) are required for in-depth analysis of the public responses to the risk perceived in the emerging drinking water quality issue.

The present study observed the current risk perception level with the presence of a low-risk perception community and a group of people who were unsure of the emerging drinking water quality issue. The situation indicates the lack of effective communication and governance in developing countries since the broad scope of EDCs had been widely detected in global drinking water supply, particularly pharmaceuticals in Malaysian tap water[39]. Further, it is not a worldwide practice to raise awareness and regulate emerging contaminants in drinking water. Subsequently, development of risk behavior (preparedness, reduction, prevention, and mitigation) and adoption of public participation in a multi-barrier approach in the monitoring and management framework of the drinking water supply system are challenging. Thus, the present study, which contributes empirical and theoretical outputs, facilitates the conceptualization of effective communication and governance, targeting the dissemination of information on safe drinking water quality and public involvement in regard to EDCs. This supports the national water sector in accomplishing the Sustainable Development Goals (SDGs) that target clean drinking water and sanitation, and safeguard public health for all.

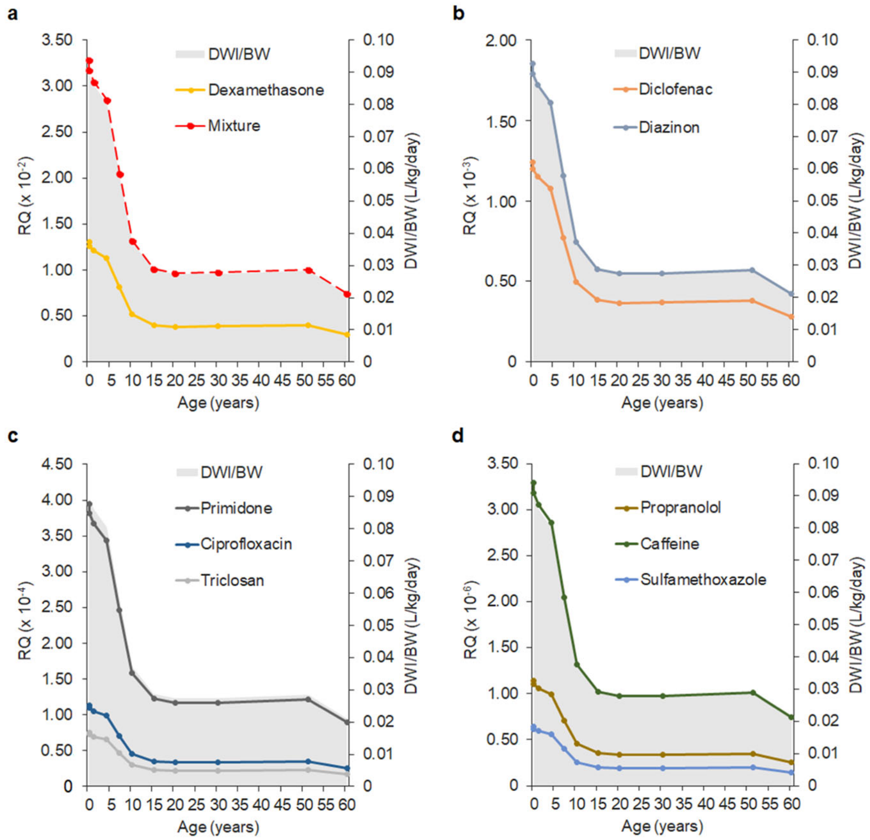

Fig. 3 Human health life-stage RQ profile of detected mixture and individual EDC residues in tap water in relation to daily water intake per body weight. There was no potential risk of EDC exposure to all the life stages via drinking water intake (RQ < 1) in the present study. **a** EDC mixture and residue with all life-stage RQs > 2.5×10^{-3}. **b** Residues with all life-stage RQs between 2.5×10^{-4} and 2.5×10^{-3}. **c** Residues with at least one life-stage RQ between 2.0×10^{-5} and 2.5×10^{-4}. **d** Residues with all life-stage RQs < 2.5×10^{-5}. DWI/BW Daily water intake per body weight, RQ Risk quotient.

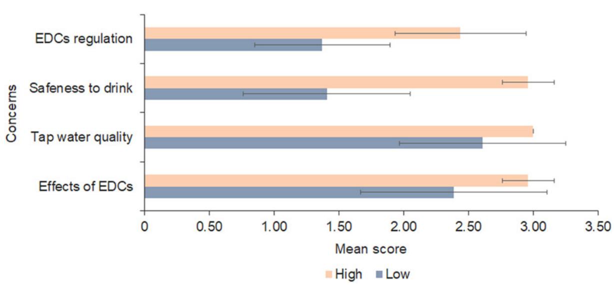

Fig. 4 Comparison of mean responses between low- and high-risk perception communities about drinking water supply quality. Error bars represent standard deviation.

METHODS

Study area

Greater Kuala Lumpur, or the Klang Valley (GKL/KV) is a National Key Economic Area with urbanization on a vast scale, holding about a quarter of the total population of Malaysia. The population in GKL/KV is projected to increase to 20 million by 2030. Putrajaya, which located in GKL/KV, is a planned city and the federal administrative centre of Malaysia, consisting of 19,511 households with approximately 88,300 people[41]. Currently, the community is exposed to EDCs, particularly pharmaceutical and personal care product residues, via daily water consumption, as reported in an earlier publication[39]. The detected EDCs including dexamethasone, primidone, propranolol, ciprofloxacin, caffeine, sulfamethoxazole, diclofenac, triclosan, and diazinon. In the study, household tap water sampling was conducted in residential areas, involving only households using tap water as drinking water supply. The analytical protocol was under quality control and assurance based on method accuracy (spiked recovery at range 85 to 146%), sensitivity (correlation coefficients >0.9), precision (relative standard deviation <15%), method detection limit (0.01 to 2.56 ng/L), and matrix effect (<100%, ionization suppression compensated using isotopically labeled compounds). Sample analyses revealed a total of nine pharmaceutical and personal care product residues (out of ten screened) from different therapeutic groups in household tap water in the range <0.03 to 21.39 ng/L, with the highest concentration observed for diclofenac (<2.56–21.39 ng/L; 6.46 ± 4.30 ng/L), an anti-inflammatory drug. Meanwhile, caffeine (0.27–5.33 ng/L; 2.39 ± 1.05 ng/L), a psychoactive stimulant that commonly utilized in pharmaceutical and food products, was present in all tap water samples and accounted for the highest distribution at 35.3%. Contamination of the monitored EDCs in tap water was speculated to be due to the inefficient conventional treatment methods presently used in the treatment plant when the EDCs were also observed in the raw water[17].

Sample size

The representative sample size (n) was determined using the sample size formula in Eq. (1)[42]. As prevalence value for EDC exposure to health is still being investigated, the nearest prevalence value (p) taken was 0.083, represents total deaths attributed to environmental exposure[43,44]. Assuming 95% confidence level ($Z = 1.96$) and 5% margin of error ($d = 0.05$), the sample size (n) is 117 respondents. An additional 20% (23.4) of the sample size (117) was required to append for adjustment of factors, inclusive of withdrawals, missing data and failure to follow up[45]. In total, the sample size of the present study was a minimum of 140 respondents after

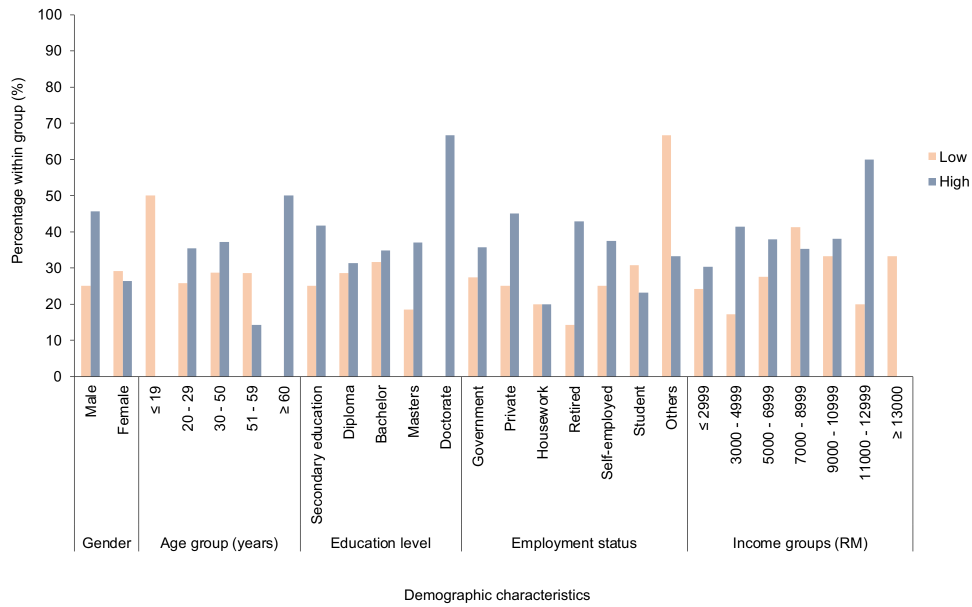

Fig. 5 Proportion of low- and high-risk perception community within different groups of demographic characteristics. The chi-square test found no significant influence of demographic characteristics in the distribution of risk perception communities ($p > 0.05$), whereby the risk processing system could be the influencing factor.

considering all the details in sample size determination.

$$n = \left(Z^2\right) \times (p(1-p))/d^2 \quad (3)$$

Questionnaire survey

In this study, the survey was conducted using a questionnaire entitled "Exposure and Risk Perception on Endocrine Disrupting Compounds (EDCs) in Malaysian Tap Water", as shown in Supplementary Information. Putrajaya residents that take drinking water from tap water were selected randomly for the survey. The questionnaires were hand delivered and distributed through online platforms. Respondents were briefed on the nature and purpose of the study, whereby they were provided an option of whether they would favor or oppose answering the survey. Sociodemographic questions (11 items i.e., gender, age, marital status, residential location, education level, employment status, household income, household size, body weight and height, and pregnancy) were for categorization purposes. While in the human exposure section, 13 closed-ended questions were completed for evaluation of consumption patterns (e.g., daily water intake, type of drinking water, and frequency of exposure) and household practices regarding the use of tap water as drinking water. Parents or guardians with infants, children, and/or adolescents were asked to answer questions about their children's exposure. Further, five-point Likert-scale (4 items) were employed to compute public-perceived effects of EDCs, tap water quality, safety of Malaysian tap water for drinking, and the capability of the Malaysia Drinking Water Quality Standard to regulate EDCs in tap water, categorizing from '1 = strongly disagree' to '5 = strongly agree'.

To ensure the readability and reliability of the questionnaire, the questionnaire was validated by experts and pre-tested before the actual study was carried out. Extant literature recommended 10% of the sample size targeted for pilots in survey research[46,47]. Nevertheless, 10 to 30 participants was also suggested as the pilot study sample size[48,49]. Thus, the pilot test was conducted on 20 residents with the same drinking water supply system. A Cronbach's alpha value of 0.935 was acquired from the pre-test, which is an acceptable value for reliability[50]. The questionnaire was intellectually protected under copyright by the Intellectual Property Corporation of Malaysia (MyIPO) through Putra Science Park (LY2018000940) and ethically approved by the Ethics Committee for Research Involving Human Subjects of Universiti Putra Malaysia (JKEUPM-2017-181). All the materials and methods were performed under relevant guidelines and regulations.

Data analysis

The statistical software IBM SPSS (Version 22.0) was utilized for descriptive and inferential statistical analysis. Descriptive statistics, for instance, mean, standard deviation, and percentage were calculated to demonstrate the demographic characteristics, human morphology, consumption patterns, household practices, and perceived risks of tap water as drinking water. Distribution of responses from questions with multiple responses was presented in percentage form based on the total number of answers provided. Inferential statistics such as one-way analysis of variance and independent *t*-test were applied for continuous data to assess the statistical significant difference. The relationship between human morphology and daily water consumption was analyzed using Pearson product-moment correlation test. Data sets were checked for normality using the Kolmogorov-Smirnov test before statistical analysis. The influence of demographic characteristics on household practices for daily drinking water consumption and distribution of risk perception communities were evaluated using a chi-square test.

DATA AVAILABILITY

All relevant data supporting the findings of this study are available within the paper and its Supplementary Information file.

CODE AVAILABILITY

No code was attempted or used during the current manuscript.

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AUTHOR CONTRIBUTIONS

S.Y.W.: Conceptualization, Methodology, Investigation, Validation, Formal analysis, Writing—Original Draft, Writing—Review & Editing, Visualization; A.Z.A.: Conceptualization, Supervision, Funding acquisition, Writing—Review & Editing; F.M.Y.: Methodology, Writing—Review & Editing; S.M.P.: Methodology, Writing—Review & Editing; R.H.: Methodology, Funding acquisition. All authors agreed with the final written version.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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