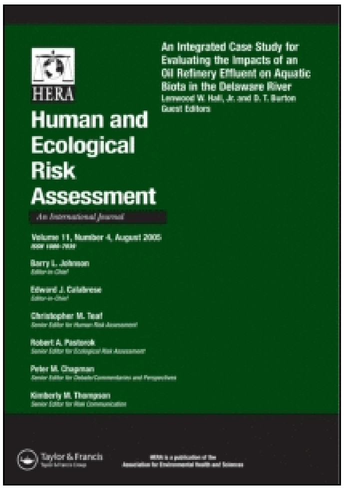

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Health Risk Assessment of Fluoride Exposure in Soil, Plants, and Water at Isfahan, Iran

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ABSTRACT

Fluoride is a potentially toxic element, with a narrow range of tolerable amounts taken up via food or drinking water. To evaluate F content in surface soils, 255 topsoil samples (0–20 cm) in an area of 6800 km^2 in Isfahan province of central Iran were collected. Crop plants and randomly sampled water samples from wells were evaluated during the spring and summer seasons. Total F concentration in 96% of soil samples was lower than the global suggested average of 200 mg kg^{-1}. The mean F concentration of water samples in the study area was 0.05 and 0.3 mg L^{-1} in summer and spring, respectively. Fluoride concentrations in different plant species were in the range of normal values. The total hazard quotient (HQ) for both population groups via consumption of cereals, vegetables, and water; incidental ingestion of soil; inhalation of soil particulates; and dermal contact with water and soil was less than 1.0, resembling no obvious risk. It is suggested that neither age group in Isfahan province will experience a significant potential health risk through their dietary intake of cereals, vegetables, and water; ingestion of soil; inhalation of particulates; and dermal contact.

Key Words: Iran, fluoride, cereal, vegetables, hazard quotient.

INTRODUCTION

Fluoride is an essential micronutrient in human diets and has both positive and negative effects on human health. Compared with many other chemicals, there is a relatively narrow range between intakes associated with beneficial effects and exposures causing adverse effects (Malinowska *et al.* 2008). Although the beneficial effects of F on human health are well accepted by the scientific community, excess F intake is not without consequence. Skeletal and dental fluorosis are examples of

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famous hazardous influences of high F concentrations in humans, affecting millions of people globally (Fomon *et al.* 2000; Jacks *et al.* 2005). Human populations in countries such as Algeria, China, Egypt, India, Iran, Jordan, Libya, New Zealand, South Africa, and Turkey have been reported to suffer from fluorosis due to intake of F-rich water (Teotia *et al.* 1981; Dissanayake 1991; Binbin *et al.* 2005; Meenakshi 2006).

Many regions in Iran are exposed to high F content in drinking water, and the occurrence of fluorosis is reported for some small towns and villages such as Borazjan, Khormoj, Maku, and Lar in Bushehr, west Azerbaijan, and Fars provinces (Asghari Moghadam and Fijani 2008). Endemic dental fluorosis has also been observed in most inhabitants of three villages of the Muteh area, located in northwest Isfahan province, with mottled enamel related to high levels of F in drinking water (1.8–2.2 ppm) (Keshavarzi *et al.* 2010).

Drinking water is the main source of F intake by humans (Edmunds and Smedley 2005) but other sources of F like F toothpaste, food grown in soil containing F or irrigated with fluoridated water, and soil contribute to the overall F intake (Karthikeyan *et al.* 1996; Fomon *et al.* 2000; Erdal and Buchanan 2005). Therefore, determination of exposure to all sources of F is important for the estimation of daily intake and consequently for the assessment of any adverse health effects.

Isfahan province is one of the most important industrial and agricultural activities centers in central Iran. There are two large steel factories in the southwest, a refinery in the northwest and a zinc–lead mine in the center of the province. In addition, there are several wastewater treatment plants and a compost factory in the region whose products (sewage sludge, treated wastewater, and compost) are used on agricultural lands (Amini *et al.* 2005a,b). The parent rock materials in the study area are mainly of recent terraces, recent alluvial deposits, and undifferentiated terraces (all of quaternary age). In addition, grey limestone containing orbitalin and shale containing ammonite (from Lower Cretaceous) have been found locally in the southwest and the south of the region (Amini *et al.* 2005a,b).

People in the region daily consume lots of vegetables, rice, and wheat. In addition, due to the hot and dry weather, water consumption is relatively high. F intake from these sources could be high, putting the people at health risk. Another source of F intake could be from soil particulate inhalation, soil ingestion and dermal contact with water and soil. Inhalation of soil particulates and soil ingestion are especially important in arid and semi-arid regions where land cover is minimal such as central Iran.

There is no information available on total F intake from major sources such as vegetables, cereals, and water and particulate inhalation by humans and the health risk associated with F in the arid and semi-arid region of Iran. Therefore, the objectives of this study were to determine (1) F concentrations in soil, water, and edible tissues of wheat, rice, and some of the most common vegetables consumed in the area, (2) total F intake and fluorosis risk of population groups using quantitative health risk assessment.

Several methods have been proposed to estimate the potential health risks of pollutants, dividing the effects into carcinogenic and non-carcinogenic (USEPA 2000a). Non-carcinogenic risk assessments are typically based on the use of the hazard quotient (HQ), a ratio of the estimated dose of a contaminant to the dose level below which there will not be any appreciable risk (Reference dose, RfD) (USEPA 2000a).

In this study, the HQ values were calculated to evaluate the non-carcinogenic health effects of F due to the ingestion of cereals, vegetables, water, and soil, dermal absorption of F from soil and water, and inhalation of soil particulates.

MATERIALS AND METHODS

Study Area and Sampling

This research was conducted in Isfahan province (east of 51°15′ to 52°41′42″ longitude and north of 32°31′30″ to 32°59′48″ latitude). The study area is about 6800 km^2 around the Zayandehroud River, which flows from west to southeast in central Iran. The region covers agricultural, industrial, and urban activities concentrated around the river and mainly in the central and western part. The eastern part is completely rural (Amini *et al*. 2005a,b).

To study the distribution of F concentrations in the region, a random unaligned sampling strategy was used. This procedure involves stratifying the region into regular-sized grid cells. Each grid cell was divided into many smaller pixels. The position of samples within each pixel is randomly chosen. The study area was divided into a regular grid of 20 × 20 km and each of those cells was divided into 16 sub-pixels (5 × 5 km). A total of 255 topsoil samples (0–20 cm) were collected from sub-pixels (Amini *et al*. 2005a,b).

Plant species, namely, rice (*Oriza sativa*), onion (*Allium cepa*), leek (*Alliums pp*), maize (*Zea mays*), potato (*Solanum tuberosum*), lettuce (*Lactuca sativa*), wheat (*Triticum sativam*), tomato (*Lycopersicum esculentum miller*), spearmint (*Mentha arvensis*) and carrot (*Daucus carota*) were collected from the fields in 25 stations within the study area. To study F concentrations in different species, three random sites were chosen for sampling within each station and samples of leaves, stems, or roots were collected (Mirghaffari and Shariatmadari 2007). Water samples were randomly collected from 25 wells during the spring and summer seasons (Mirghaffari and Shariatmadari 2007). Drinking water samples were also randomly collected from 20 locations in Isfahan province.

Chemical Analysis

Soil samples were air dried and passed through a 2 mm sieve. For total F analysis in soil and plant samples the NaOH fusion method (McQuaker and Gurney 1977) was used. Soluble F in the soil was extracted using dionized water (1:1) (Brewer 1965). Soluble F and water F concentrations were measured using a F ion selective electrode (Metrohm AG, Switzerland) and a calomel reference electrode. Water samples were also analyzed for hardness (Clesceri *et al*. 1999), EC (1:2.5 soil to water), and pH (1:2.5 soil to water).

Data Analysis

The distribution of F in soil was characterized using the Kolmogrov-Smirnov (K-S) test for goodness-of-fit to ensure normal distribution of datasets (Sokal and

Rohlf 1981). Descriptive statistic variables including mean, variance, maximum, minimum, coefficient of variation (CV), and skewness were calculated using the statistical analysis system (SPSS) 17.

Exposure and Risk Assessment

Hazard identification

Fluorosis is a slow, progressive, crippling malady, which affects every organ, tissue, and cell in the body and results in health complaints having overlapping manifestations with several other diseases. The primary adverse effects associated with chronic, excess F intake are dental and skeletal fluorosis (Susheela 2000). It also adversely affects foetal cerebral function and neurotransmitters (Yu *et al*. 1996). Reduced intelligence in children is associated with exposure to high F levels in food and drinking water (Xiang *et al*. 2003).

Dose–response assessment

The standard procedure for a toxicity assessment is to identify toxicity values for carcinogenic and non-carcinogenic effects. Theoretically, these toxicity values can be used to evaluate toxicity that could result from oral and dermal exposure to chemicals or their inhalation. The U.S. Environmental Protection Agency's (USEPA's) derived toxicity value used in non-cancer risk assessments is termed the reference dose (RfD). In general, the RfD is an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. The USEPA (2000a) derived an oral reference dose (RfD_o) of 0.06 mg kg^{-1} day^{-1} for F. The Risk Assessment Integration System website (RAIS 2007) derived an absorbed reference dose (RfD_{ABS}) of 5.82×10^{-2} mg kg^{-1} day^{-1} for F.

Exposure assessment

Oral exposure assessment. The populations of interest in this analysis were children (<7 years of age), and adults (18–54 years of age). Equation (1) was used to calculate an estimated daily intake (EDI) for each exposure pathway (USEPA 1992).

$$EDI = C \times IR \times EF \times ED \times AF \times CF/BW \times AT \quad (1)$$

where EDI = estimated daily intake (mg kg^{-1} day^{-1}), C = concentration in a specific medium (mg L^{-1} or mg kg^{-1}), IR = ingestion or intake rate (mg day^{-1}), EF = exposure frequency (days yr^{-1}), ED = exposure duration (yr), AF = absorption factor (unit less), CF = conversion factor (10^{-6} kg mg^{-1}), BW = bodyweight (kg), AT (days) = 365 (days yr^{-1}) × ED (yr) for non-cancer hazard assessment.

The exposure pathways considered were: ingestion of non-fluoridated drinking water, consumption of foods, and incidental ingestion of soil. Using Equation (1), the EDI for each exposure route was calculated by identifying appropriate values for each exposure parameters (*e.g.,* concentration, ingestion rate, bodyweight) for each age group. Central tendency exposure (CTE) and reasonable maximum exposure (RME) values were used in characterizing potential exposures for each ingestion rate (USEPA 1989).

The age-specific values used for calculating EDI are listed in Table 1. The estimation of daily intake or ingestion rate via all the exposure media were from Mohamadifard *et al.* (2006) and the USEPA (2002a). Exposure frequency (EF) describes the number of days per year in which water and food are consumed. In this study the EF was assumed to be 365 days per year. The exposure duration (ED) values used in the intake calculations were: 3 years for children (boys/girls) and 27 years for average men and women presumably of ages 18 to 54. The absorption factor (AF) was assumed to be 100% (ATSDR 2003; Ekstrand and Ehrnebo 1980). Individual bodyweight (BW) for children and adults was considered to be 16.95, and 62.5, respectively (USEPA 1997). The averaging time (AT) was averaged over a specified period of time. In general, AT is the product of ED and 365 days/year for non-carcinogenic effects.

Dermal exposure assessment. Evaluation of exposure for the dermal route is typically based on an estimated dermal absorbed dose (DAD). Dermal absorbed dose was calculated for inorganic chemicals for two exposure media (water and soil) using Equation (2) (USEPA 2004).

$$DAD = DA_{event} \times EV \times ED \times EF \times SA/(BW \times AT) \quad (2)$$

where DAD = dermal absorbed dose (mg kg^{-1} day^{-1}), DA_{event} = absorbed dose per event (mg $cm^{-2}event^{-1}$), SA = skin surface area available for contact (cm^2), EV = event frequency (event day^{-1}), EF = exposure frequency (days $year^{-1}$), ED = exposure duration (years), BW = bodyweight (kg), AT (days) = 365 (days yr^{-1}) × ED (yr) for non-cancer hazard assessment.

In Tables 2 and 3 are summarized the default exposure values for estimated dermal absorbed dose for adults and children in water (USEPA 2004) and soil (USEPA 2004) exposure media, respectively. The skin surface area (SA) parameter describes the amount of skin exposed to the contaminated media. For dermal contact with water, the total body surface area for adults and children is assumed to be exposed for showering/bathing (USEPA 2004). In cases of soil contact, clothing is expected to limit the extent of the exposed surface area. The recommended SA exposed to contaminated soil for the adult and child residents are 5700 and 2800 cm^2, respectively (Table 3) (USEPA 2004).

Equations (3) and (4) were used to evaluate the dermal absorbed dose per event (DA_{event}) for chemicals in water and soil, respectively (USEPA 2004).

$$DA_{event} = K_p \times C_w \times t_{event} \quad (3)$$

where DA_{event} = absorbed dose per event (mg $cm^{-2}event^{-1}$), C_w = chemical concentration in water (mg cm^{-3}), t_{event} = event duration (hr $event^{-1}$), K_p = dermal permeability coefficient of compound in water (cm hr^{-1}). The permeability coefficient of 1×10^{-3} cm hr^{-1} is recommended as a default value for all inorganics.

$$DA_{event} = C_{soil} \times CF \times AF \times ABS_d \quad (4)$$

Table 1. Summary of exposure parameters used in the calculation of estimated daily fluoride intake.

Exposure medium	F concentration	CTE intake rate[a]	RME intake rate[b]
Drinking water	0.3 mg L^{-1}	Children: 0.4 L day^{-1} (USEPA 2002) Adults: 1.5 L day^{-1}	Children: 0.9 L day^{-1} (USEPA 2002) Adults: 2 L day^{-1}
Rice	1.6 (mg kg^{-1} wet weight)	Children: 27 g day^{-1} (Mohammadifard *et al.* 2006) Adults: 110 g day^{-1}	Children: 41 g day^{-1} (Mohammadifard *et al.* 2006) Adults: 165 g day^{-1}
Wheat	2.8 (mg kg^{-1} wet weight)	Children: 30 g day^{-1} (Mohammadifard *et al.* 2006) Adults: 110 g day^{-1}	Children: 45 g day^{-1} (Mohammadifard *et al.* 2006) Adults: 160 g day^{-1}
Onion	1.3 (mg kg^{-1} wet weight)	Children: 2.9 g day^{-1} (Mohammadifard *et al.* 2006) Adults: 19.2 g day^{-1}	Children: – (Mohammadifard *et al.* 2006) Adults: 27.5 g day^{-1}
Leek	1.3 (mg kg^{-1} wet weight)	Children: 1 g day^{-1} (Mohammadifard *et al.* 2006) Adults: 19.9 g day^{-1}	Children: – (Mohammadifard *et al.* 2006) Adults: 30.7 g day^{-1}
Spearmint	1.4 (mg kg^{-1} wet weight)	Children: 2 g day^{-1} (Mohammadifard *et al.* 2006) Adults: 9 g day^{-1}	Children: 4 g day^{-1} (Mohammadifard *et al.* 2006) Adults: 12 g day^{-1}

(Continued on next page)

Table 1. Summary of exposure parameters used in the calculation of estimated daily fluoride intake. *(Continued)*

Exposure medium	F concentration	CTE intake rate[a]	RME intake rate[b]
Maize	2.6 (mg kg^{-1} wet weight)	Children: 1.5 g day^{-1} (Mohammadifard *et al.* 2006) Adults: 5.7 g day^{-1}	Children: 3.4g day^{-1} (Mohammadifard *et al.* 2006) Adults: 13.7 g day^{-1}
Potato	1.4 (mg kg^{-1} wet weight)	Children: 5.6 g day^{-1} (Mohammadifard *et al.* 2006) Adults: 16.8 g day^{-1}	Children:10.4 g day^{-1} (Mohammadifard *et al.* 2006) Adults: 31.1 g day^{-1}
Lettuce	1 (mg kg^{-1} wet weight)	Children: 7.3 g day^{-1} (Mohammadifard *et al.* 2006) Adults: 29.3 g day^{-1}	Children:11.5gday^{-1} (Mohammadifard *et al.* 2006) Adults: 46.6 g day^{-1}
tomato	1.8 (mg kg^{-1} wet weight)	Children: 20 g day^{-1} (Mohammadifard *et al.* 2006) Adults: 67.7 g day^{-1}	Children: 30 g day^{-1} (Mohammadifard *et al.* 2006) Adults: 118.7 g day^{-1}
Carrot	0.5 (mg kg^{-1} wet weight)	Children: 2.9 g day^{-1} (Mohammadifard *et al.* 2006) Adults: 8 g day^{-1}	Children:3.7g day^{-1} (Mohammadifard *et al.* 2006) Adults: 14.8 g day^{-1}
Soil	100.7 $mgkg^{-1}$	Children: 0.1 g day^{-1} (USEPA 2002) Adults: 0.1 g day^{-1}	Children: 0.4 g day^{-1} (USEPA 2002) Adults: —

[a]Recommended mean intake rate as a combined estimate for males and females was used in all cases in the CTE scenario.
[b]90th percentile or maximum of recommended intake rate was used in the RME scenario.

Table 2. Recommended dermal exposure values for CTE and RME residential scenario-water content.

Exposure parameters	CTE Showering/ Bathing	RME Showering/ Bathing
Event frequency (event day^{-1})	1	1
Exposure frequency (days yr^{-1})	350	350
Event duration (hr $event^{-1}$)		
Adult	0.25	0.58
Child	0.33	1
Exposure duration (yr)		
Adult	9	30
Child	6	6
Skin surface area available for contact (cm^2)		
Adult	18,000	18,000
Child	6600	6600

where C_{soil} = chemical concentration in soil (mg kg^{-1}), CF = conversion factor (10^{-6} kg mg^{-1}), AF = adherence factor of soil to skin (mg $cm^{-2}event^{-1}$), ABS_d = dermal absorption fraction. The default ABS_d assumptions are based on USEPA Region 4 (USEPA 2000b) guidance recommending a value of 0.001 for inorganic chemicals.

Particulate inhalation exposure assessment. Inhalation of soil particulates was calculated as follows:

$$(CDI)\,(mg/kg\text{-}day) = CS \times (1/PEF) \times IN \times F_{Inh} \times EF \times ED/BW \times AT \quad (5)$$

where CDI = chronic daily intake (mg kg^{-1} day^{-1}), CS = chemical concentration in soil (mg kg^{-1}), PEF = particulate emission factor (m^3 kg^{-1}), IN = inhalation rate (m^3 day^{-1}), F_{Inh} = fraction inhaled, EF = exposure frequency (days $year^{-1}$), ED = exposure duration (years), BW = bodyweight (kg), AT = averaging time (days).

Table 3. Recommended dermal exposure values for CTE and RME residential scenario-soil content.

Exposure parameters	CTE	RME
Event frequency (event day^{-1})	1	1
Exposure frequency (days yr^{-1})	350	350
Exposure duration (yr)	9	30
Dermal absorption factor	0.001	0.001
Skin surface area available for contact (cm^2)		
Adult	5700	5700
Child	2800	2800
Soil adherence factor (mg cm^{-2})		
Adult	0.01	0.07
Child	0.04	0.2

In this study, inhalation rate (IN) was considered to be 10 m^3 day^{-1} for children and 20 m^3 day^{-1} for adults (USEPA 1997). PEF, EF, and F_{Inh} were assumed to be 1.20E+09 (USEPA 2002b), 350 days per year (USEPA 1991), and 1 (USEPA 2002b), respectively. In addition, ED was considered to be 6 for children and 24 for adults (USEPA 1991). The AT and BW values used to estimate particulate inhalation were similar to Equation (1).

Risk characterization

Hazard quotients (HQs) for ingestion (USEPA 1989), dermal contact (USEPA 1989), and particulate inhalation (USEPA 1989) were calculated as follows:

$$HQ = EDI/RfD_o \tag{6}$$

$$\text{Dermal Hazard Quotient} = DAD/RfD_{ABS} \tag{7}$$

$$RfD_{ABS} = RfD_o \times ABS_{GI} \tag{8}$$

$$\text{Inhalation Hazard Quotient} = CDI/RfD_{ABS} \tag{9}$$

where EDI = exposure level (or intake) (mg kg^{-1} day^{-1}), RfD_o = oral reference dose (mg kg^{-1} day^{-1}), which was considered to be 0.06 mg kg^{-1} day^{-1} for F (USEPA 2000a), DAD = dermal absorbed dose (mg kg^{-1} day^{-1}), RfD_{ABS} = absorbed reference dose (mg $kg^{-1}day^{-1}$) (absorbed reference dose can be calculated from the oral toxicity values as presented in Equation (8)), ABS_{GI} = fraction of contaminant absorbed in gastrointestinal tract in the critical toxicity study that was assumed to be 0.97 for F (CTLs 2005), CDI = chronic daily intake (mg kg^{-1} day^{-1}).

When the HQ is greater than 1.0, the estimated potential exposure exceeds the RfD and a potential risk may exist for the endpoint evaluated (Barnes and Dourson 1988).

RESULTS AND DISCUSSION

Fluoride Concentration in Soil

The total F content of surface soil ranged from 6.4 to 264.9 mg kg^{-1} with a mean of 100.7 ±53.2 mg kg^{-1} in the study area (Table 4). The regional mean of total F content is less than the world average total F content in soil, which is 200 mg kg^{-1} (CNEMS 1990). There were significant differences (0.01 levels) between land uses for total F concentrations (Table 4). Fluoride concentrations in agricultural and urban areas were significantly greater than uncultivated lands due to the industrial and agricultural activities in the region. Loganathan *et al.* (2001) reported that long-term phosphorus fertilization was the main reason for the greater F content of the pasture soils of New Zealand. However, the exact increase in soil F concentration in each region depends on the F concentration in the native soil and fertilizer history. The relative contribution of these two factors cannot be accurately determined in this study area because the fertilizer history and F concentration in the native soil are not accurately known.

Another major source of F is air pollution that can affect plant and animal life through the air and by accumulation in soil. Phosphate fertilizers and aluminum

Table 4. Statistical summary of total soil fluoride in Isfahan province.

	Agricultural (% of the data 46) Total F	Urban (% of the data 9) Total F	Uncultivated (% of the data 45) Total F	Total (% of the data 100) Total F
Mean	106.7a	111.9a	92.6b	100.7
Min	6.4	11.9	7.6	6.4
Max	264.9	202.3	221.3	264.9
Range	258.5	190.4	213.7	258.5
S.D	56.4	60.4	47.3	53.2
C.V	1.9	1.8	1.9	1.9

*Values with the same letter are not significantly different at $p = .01$.

smelting plus factories producing fertilizers, glass, and steel can be the sources of F pollution locally (Cronin *et al.* 2000). There are two big steel factories in the southwest, a refinery in the northwest, and a lead mine in the central part of the study area. These factories are the sources of F emission in this region. However, there are no data available on gaseous F emitted from the industrial sources in the region.

Fluoride Concentration in Groundwater

The summary statistics of chemical composition of groundwater are presented in Table 5 (Mirghaffari and Shariatmadari 2007). Average F concentration in groundwater samples during summer and spring seasons were 0.05 and 0.3 mg L^{-1}, respectively (Mirghaffari and Shariatmadari 2007). Average F concentration in drinking water samples were also 0.3 mg L^{-1}, which is less than the standard level of 1.5 mg L^{-1} (WHO 2004).

Two parameters of water quality, EC and hardness (Ca and Mg), and F concentration were analyzed in both wet (spring) and dry (summer) periods of the year.

Table 5. Fluoride concentration and water characteristics of the groundwater in Isfahan province.

Season	Fluoride (mg L^{-1})	EC (dS m^{-1})	pH	Hardness (mg L^{-1})
Spring				
Mean	0.3a	2.3b	8.7	741.5b
Min	0.09	0.5	7.9	220
Max	0.4	6.2	9	1216
SD	0.1	1.5	0.3	277
Summer				
Mean	0.05*b*	4a	8.2	913.9*a*
Min	0.01	0.3	7.8	220
Max	0.1	10.9	8.8	2472
SD	0.03	2.6	0.2	648.5

*Values with the same letter within each column are not significantly different at $p = .05$.

Table 6. Fluoride concentration in edible parts of selected plants (μg g^{-1} of dry weight).

Plant	Scientific name	Mean	SD
Rice	*Oriza sativa*	1.9	1.5
Onion	*Allium cepa*	2.5	1.2
Leek	*Alliums pp*	2.4	1.5
Maize	*Zea mays*	2.9	1.9
Potato	*Solanum tuberosum*	2.6	1.1
Lettuce	*Lactuca sativa*	2	0.5
Wheat	*Triticum sativam*	3.2	1.1
Tomato	*Lycopersicum esculentum miller*	3.6	0.5
Spearmint	*Mentha arvensis*	2.6	1.2
Carrot	*Daucus carota*	1	0.001

Hardness, EC, and F content in groundwater samples were significantly different (0.05 levels) between the two sampling periods (Table 5). Results showed that due to precipitation as well as snow melting in spring, these parameters were lower in summer, when water is mainly discharged for irrigation. The lower F content of groundwater in summer is also probably because of the formation of insoluble fluorite (CaF_2) formed through increasing Ca^{2+} (Saxena and Ahmed 2003). Fluorite is the predominant mineral that controls the dissolved F concentration in groundwater (Saxena and Ahmed 2003; Edmunds and Smedley 2005).

Fluoride Concentration in Plant Tissues

Fluoride concentrations in different plant species are presented in Table 6 (Mirghaffari and Shariatmadari 2007). These values were in the range of the normal values, which for the leaves generally range from 1 to 10 μg g^{-1} dry weight (Vike 1999).

The most important factor controlling F uptake from soil is the low solubility of soil F. According to Weinstein (1977), plants growing in soils that contain up to about 600–800 mg kg^{-1} F usually have F in leaves from <2 to about 20 μg g^{-1}.

The water soluble F in the study area ranged from 0.1 to 3.9 mg kg^{-1} with a mean of 0.9 $\pm$ 0.6 mg kg^{-1}, which constituted 1.5% of the total F. There is a significant correlation (at 0.01 levels) between the F content in vegetation and water soluble F in soils, which is in agreement with earlier finding (Stevens *et al.* 1998; Jha *et al.* 2008).

Daily Intake of F

The daily intake estimates for CTE and RME exposure scenarios for each route and for both age groups are shown in Table 7. The cumulative daily F intake through consumption of cereals, vegetables, water, and incidental ingestion of soil are 18.7, and 19.2 μg kg^{-1} day^{-1} for the CTE scenario, for children and adults, respectively, This is in agreement with earlier findings (Kimura *et al.* 2001; Murakami *et al.* 2002).

Table 7. EDI (μg kg^{-1} day^{-1}) estimates for CTE and RME Ingestion, dermal contact, and particulate inhalation exposure scenarios.

	CTE		RME	
Exposure medium	Children	Adults	Children	Adults
Rice	2.5	2.8	3.9	4.2
Wheat	4.9	4.9	7.2	7.2
Onion	0.2	0.4	0.3	0.6
Leek	0.07	0.4	0.2	0.6
Spearmint	0.2	0.2	0.3	0.3
Maize	0.2	0.2	0.5	0.6
Potato	0.5	0.4	0.8	0.7
Lettuce	0.4	0.5	0.7	0.7
Tomato	2.1	1.9	3.2	3.4
Carrot	0.08	0.06	0.1	0.1
Water				
Ingestion	7	7.2	15	9.6
Dermal contact	$3.7 \times 10{-}2$	$2 \times 10{-}2$	$1.1 \times 10{-}1$	$4.8 \times 10{-}2$
Soil				
Ingestion	0.6	0.2	2.4	NA
Dermal contact	$6.3 \times 10{-}4$	$8.8 \times 10{-}5$	$3.2 \times 10{-}3$	$6.1 \times 10{-}4$
Particulate inhalation			$4.7 \times 10{-}5$	$2.2 \times 10{-}6$

NA: exposure routes assumed to be not applicable.

Kimura *et al.* (2001) found that children aged 2–6 years ingested 15–21 μg F kg^{-1} day^{-1} and Murakami *et al.* (2002) reported that children aged 3–5 years ingested 16–20 μg F kg^{-1} day^{-1} from their diet alone.

Drinking water (37%), wheat (26%), rice (14%), and tomato (10%) are the most significant sources contributing to cumulative daily F intake for both age groups. Moreover, the daily intakes of F through incidental ingestion of soil were 3.2% and 1% of the cumulative intake for children and adults, respectively. These results show that drinking water is the main source of F intake among the people of the region.

The RME EDI estimates for cereals, vegetables, water, and incidental ingestion soil exposure routes were 34.6 and 28 μg kg^{-1} day^{-1} for children and adults, respectively. These values are less than the dietary reference intake (DRI). The DRI value is the adequate intake (AI) that establishes a goal for intake to sustain a desired indicator of health without causing side effects (IOM 1997). The AI for F from all sources (water, food, beverages, fluoride dental products, and daily fluoride supplement) is set at 50 μg kg^{-1} of bodyweight day^{-1} (IOM 1997).

The dietary intakes of F for children and adults is less than the upper intake level (UL) of 100 μg kg^{-1} day^{-1} (IOM 1997) for children through 8 years of age and 1000 μg kg^{-1} day^{-1} for adults, regardless of weight (IOM 1997). The UL is the established maximum intake level that should not produce unwanted effects on health. The results show that F deficiency is probably more important than F toxicity in the region.

Uptake of F through Dermal Contact and Particulate Inhalation

The estimated dermal absorbed doses for CTE and RME exposure scenarios for soil and water exposure media for both age groups are shown in Table 7. The estimated DAD of F for water exposure is similar to those reported by Zabin *et al.* (2008) for children and adults in the Al-Bahan region, Saudi Arabia.

The DAD of F through water exposure constitutes about 0.5–0.7% and 0.2–0.5% of the total daily intake of water for both routes (ingestion and dermal contact) for children and adults, respectively. Dermal contact with soil also constitutes about 0.1% and 0.04% of the cumulative daily intake of F through incidental ingestion of soil, inhalation of soil particulate and dermal uptake for children and adults, respectively. Particulate inhalation route of exposure is negligible compared to the ingestion route of exposure (Table 7) and constitutes about 0.001% of the cumulative daily intake of F via soil.

The estimated dermal absorbed dose values for F (Table 7) for two exposure media and the estimated particulate inhalation values for F are less than the absorbed reference dose of 58.2 μg kg^{-1} day^{-1}. The results showed that there are not any non-carcinogenic health effect through dermal absorption and particulate inhalation in the region.

Potential Health Risk of F

The HQ values of F for the two age groups and each exposure scenario are listed in Table 8. All the HQ values are less than unity for CTE and RME estimates.

Table 8. The CTE and RME HQ estimates for ingestion, dermal contact, and particulate inhalation exposure pathways.

	CTE		RME	
Exposure medium	Children	Adults	Children	Adults
Rice	4×10^{-2}	5×10^{-2}	6×10^{-2}	7×10^{-2}
Wheat	8×10^{-2}	8×10^{-2}	1×10^{-1}	1×10^{-1}
Onion	3.3×10^{-3}	6.7×10^{-3}	5×10^{-3}	1×10^{-2}
Leek	1.2×10^{-3}	6.7×10^{-3}	3.3×10^{-3}	1×10^{-2}
Spearmint	3.3×10^{-3}	3.3×10^{-3}	5×10^{-3}	5×10^{-3}
Maize	3.3×10^{-3}	3.3×10^{-3}	8.3×10^{-3}	1×10^{-2}
Potato	8.3×10^{-3}	6.7×10^{-3}	1×10^{-2}	1×10^{-2}
Lettuce	6.7×10^{-3}	8.3×10^{-3}	1×10^{-2}	1×10^{-2}
Tomato	3×10^{-2}	3×10^{-2}	5×10^{-2}	6×10^{-2}
Carrot	1.3×10^{-3}	1×10^{-3}	1.7×10^{-3}	1.7×10^{-3}
Water				
Ingestion	1×10^{-1}	1×10^{-1}	2×10^{-1}	2×10^{-1}
Dermal contact	6.3×10^{-4}	3.4×10^{-4}	1.8×10^{-3}	8.2×10^{-4}
Soil				
Ingestion	1×10^{-2}	3.3×10^{-3}	4×10^{-2}	NA
Dermal contact	1×10^{-5}	1.5×10^{-6}	0.5×10^{-4}	1×10^{-5}
Particulate inhalation			8×10^{-7}	3.8×10^{-8}

NA: exposure routes assumed to be not applicable.

This result indicates that health risks associated with F exposure for children and adults are insignificant if the resident's F intake is only from water, soil, cereals, and vegetables (Table 8). The HQ estimates for the RME scenario are less than 1, indicating that cumulative daily F intake is less than the safe dose level (60 μg kg^{-1} day^{-1}) established by the USEPA for F (USEPA 2000a). It is suggested that neither age group in the region will be confronted with a significant potential health risk by incidental ingestion of soil, dermal contact with water and soil, particulate inhalation, intake of water and consumption of their cereals or vegetables. However, other important sources of F such as tea, sea products, and toothpaste have not been used in our calculations in this study, which could significantly increase HQ values. The findings of this study confirm the importance of considering all potentially applicable exposure routes in estimating cumulative daily F dose for scientifically sound decision-making in fluorosis risk management.

CONCLUSION

Fluoride concentrations in soil, water, and edible tissues of wheat, rice, and some of the most common vegetables consumed in Isfahan province were investigated. The results showed that nearly 96% of soil samples had F concentration less than 200 mg kg^{-1}, which is reported as the world average F concentration in soils (CNEMS 1990). Fluoride concentration in groundwater and drinking water was less than the standard level (1.5 mg L^{-1}) suggested by the World Health Organization (WHO 2004). The level of F determined in many vegetables and cereals grown in Isfahan were within the normal F content in plants.

The non-carcinogenic health risks posed by exposure to F of different population groups through the consumption of cereals, vegetables, water, inhalation of soil particulate, and dermal contact with water and soil in central Iran were investigated based on estimated hazard quotients (HQ). The results showed that the ingestion route of exposure will have a relatively greater HQ while the risks contributed by particulate inhalation and dermal contact are minimal and only account for a negligible fraction of calculated total HQ. On the other hand, the total HQ values are less than 1 for both population groups.

The risk estimates were all qualitative due to the uncertainties of some data in this study similar to the adherence factor and the value used to represent the concentration in soil for the dermal–soil exposure route, the K_p and the value used to represent the concentration in water for the dermal–water exposure route, the U.S. biometric data for some populations group including bodyweight and local information for intake rate, and exposure frequency assumption. The variability of F in the studied plant species as affected by different management and other factors may affect the risk of F for the population. For this purpose, we assumed a constant water, vegetables, and cereals daily intake rate over a lifetime, while in fact many factors affect the daily intake of people.

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