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Microbial contamination in surface water and potential health risks for peri-urban farmers of the Bengal delta

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ABSTRACT

Ensuring safe irrigation practices is vital to sustaining food production in water-scarce delta areas. Bangladesh and many other developing countries discharge untreated wastewater into their surrounding surface water bodies, serving as the primary irrigation source. This indirect irrigation of wastewater is believed to pose threats to the farmers, consumers and market vendors and may also affect crop and soil quality. To assess the risk, peri-urban farmers who use surrounding water bodies of Khulna city, Bangladesh, for crop irrigation were selected for the study. The microbial and heavy metal concentrations were measured in water samples collected from various locations over different seasons. For heavy metals As, Co, Ni, Cd, Cr, Cu and Pb, concentrations were below the detection limit, whereas Al, Fe, Mn, Ti and Zn were present but below the FAO recommendation limit for safe irrigation. The mean concentrations of microbial parameters were above the thresholds of WHO guidelines for crop irrigation intended for human consumption. Significant temporal variations in Faecal Coliform, *E. coli* and *Enterococcus* concentrations in the water samples were observed. The annual risk of infection for farmers was determined using the screening-level Quantitative Microbial Risk Assessment (QMRA). The results indicated that the annual probability of infection with pathogenic *E. coli* in different seasons ranges between 5×10^{-3} to 5×10^{-2}, above the WHO's acceptable threshold for annual risk of infection for safe water reuse in agriculture. During the farmers' survey, around 45% reported health-related issues and more than 26% reported suffering from water-borne diseases after getting in contact with polluted surface water. This illustrates the actuality of the risks in practice. To ensure safe irrigation, the health risks need to be reduced below the acceptable limits. Suggested technical measures include adequate treatment of wastewater before disposal into rivers and access to protective equipment for farmers. This should be complemented by raising awareness through education programs among farmers to reduce accidental ingestion.

1. Introduction

Global water scarcity is aggravated by the growing water demand caused by increasing populations and climate change (Mekonnen and Hoekstra, 2016). This issue is more clearly visible in the urbanizing delta such as the Bengal delta, which is also severely confronted with freshwater scarcity (Murshed and Kaluarachchi, 2018). In most situations, current water resource management practices in urban areas are linear and waste valuable resources such as water and nutrients. Though some countries have close to 100% coverage in collecting and treating urban wastewaters, only around 63% of the total wastewater generated globally is collected and 48% is discharged without treatment, which deteriorates the surface water quality (Jones et al., 2021; Kookana et al., 2020). Urban water reuse, in general, has been practiced globally to make this water reusable for irrigation and to mitigate the impact of freshwater scarcity on food production.

The use of wastewater for irrigation has gained attention during the last decade of the twentieth century because of the growing demands for irrigation and the raising concerns over the health effects to farmers and consumers (Jaramillo and Restrepo, 2017). For decades, farmers in Jordan and Israel have utilized wastewater for agricultural production due to the minimal local availability of water resources (Angelakis and Gikas, 2014; Carr et al., 2011). The examples in these countries

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List of abbreviations

CFU	Colony Forming Unit
DALYs	Disability Adjusted Life Years
FAO	Food and Agriculture Organization
FIB	Faecal Indicator Bacteria
GoB	Government of Bangladesh
MF	Membrane Filtration
QMRA	Quantitative Microbial Risk Assessment
WHO	World Health Organization
TC	Total coliform
FC	Faecal coliform
E. coli	*Escherichia coli*
Al	Aluminum
As	Arsenic
Cd	Cadmium
Cr	Chromium
Co	Cobalt
Cu	Copper
Fe	Iron
Pb	Lead
Mn	Manganese
Ni	Nickel
Ti	Titanium
Zn	Zinc

demonstrate good treated wastewater irrigation practices that also minimize the health risks. But these practices are not yet applied in many regions of the world. The use of untreated wastewater for irrigation can negatively impact human health as well as the quality of the environment (including soils) and crops. Wastewater commonly contains excreta-related pathogens (e.g. bacteria, viruses, protozoa and helminths) and toxic chemicals, such as heavy metals and micropollutants (e.g. pesticides, household chemicals, pharmaceutical residues) (Drechsel et al., 2010a; Gross et al., 2015; Jiménez and Asano, 2008; Mojid and Wyseure, 2013). In developing countries especially, untreated wastewater is discharged into the natural surface water streams which are major sources for irrigating crops. As a result, farmers and consumers are regularly exposed to unknown chemical and biological pollution.

To minimize the health risks due to the increasing unplanned and indirect wastewater irrigation practices, several risk assessments such as sanitary inspection, risk matrix, Quantitive Microbial Risk Assessment (QMRA) and risk mitigation frameworks such as Stockholm framework, sanitation safety planning, multiple-barrier approach have been drafted and used (WHO, 2006). These approaches are briefly discussed further in the manuscript. Sanitary inspection is an on-site visual evaluation tool, whereas the risk matrix approach provides a semi-quantitative and qualitative evaluation of the likelihood of a hazardous event. QMRA is a tool used for predicting the risk of infection or illness rates of humans exposed to pathogens, by using ingestion probability estimations and dose-response models based on a given population (Ferrer et al., 2012; Haas et al., 1999). QMRA is the formal WHO-approved quantitative risk assessment approach that integrates the scientific knowledge on the infectious effects of pathogens present in the water (WHO, 2016). The numerical outcomes of QMRA bring more specific insights useful for risk management as compared to other methods such as sanitary inspection and risk matrix (WHO, 2016). Though less sensitive, QMRA is less costly and less time-consuming than epidemiological studies and therefore, has become a preferred method for application (Ferrer et al., 2012). However, QMRA is a standardized model that is only applicable to a limited range of pathogens and is not yet developed to address the full range of pathogens actually present in wastewater, restricting its wider use for risk assessment (Hamilton and Haas, 2016). The Stockholm framework improved health-related guidelines and standards through a coherent system (WHO, 2006). Similarly, the multiple barrier approach is a risk mitigation framework that combines technical and non-technical strategies for risk mitigation and complements the sub-optimal wastewater treatment, which is seen as the best possible approach to reduce risks (Bos et al., 2010; Keraita et al., 2008; WHO, 2006). The multiple barrier approach stretches from wastewater generation to the consumption of irrigated crops (i.e. from farm to fork) and is vital for strategizing safe water reuse practices. This is crucial, especially for many urbanized deltas in developing and emerging economies where untreated urban wastewaters are regularly dumped into the rivers flowing to the sea. Meanwhile the very same water is also needed for irrigation to combat with the rising salinization.

Khulna: the third largest city of Bangladesh and has been taken as an example to assess the health risks (to later define risk mitigation) of the irrigation practices in urbanized deltas. The presence of elevated pathogen levels in surface water bodies due to anthropogenic activities has been reported in the coastal region of Bangladesh (Islam et al., 2017, 2018a, 2018b). Peri-urban agriculture in the delta area contributes to regional food production and surface water is the primary source of irrigation. Peri-urban farmers around the country have reported skin irritation, itchiness in the hands and legs while working with the surface water (Mojid et al., 2010). These effects are suspected to be related to untreated wastewater discharge in surface waters. Aside from skin contact, there is also a high probability that farmers and their family members have had contact with the wastewater pollutants through ingestion or aerosol inhalation (An et al., 2007). Several studies focused on assessing the health risks associated with river bathing or urban flooding; however, risk assessment related to indirect wastewater irrigation is scarce (Islam and Islam, 2020; Mark et al., 2018). Thus, there is a need to investigate the actual wastewater-related pollutant concentrations in surface waters and link these to actual risks for farmers as a base to design adequate risk mitigation measures. Faecal Indicator Bacteria (FIB) are widely used to understand the presence of pathogenic microorganisms in water (WHO, 2002). *E. coli*, faecal coliforms and faecal streptococci (with *enterococci* as subgroup) are commonly used as FIB (Islam et al., 2017). FIB could be useful to understand the microbial water quality and to formulate necessary risk mitigation strategies (Islam et al., 2017; Maimon et al., 2010; Teklehaimanot et al., 2014; Wu et al., 2011).

The first step in any set of measures is to mitigate risks due to direct or indirect use of wastewater for irrigation. This can first be approached by assessing the risks associated with pathogens, heavy metals and other (organic) chemical pollutants. In this study, the first steps of pollutant characterization were performed based on the local laboratory capacity. Therefore a set of selected microbial pathogens as indicators for domestic wastewater pollution and a suite of heavy metals as an indicator of industrial pollution is discussed in this study. The microbial contamination in surface water was evaluated and potential health risk for farmers was assessed assuming continuous exposure to pollutants in wastewater indirectly used for irrigation. Additionally, the farmers' risk perception towards the current irrigation practice was analyzed to address the required management strategies, including both technical and non-technical measures to reduce the risk of infection.

2. Methodology

2.1. Study area and sampling sites

Khulna City is positioned on the banks of rivers Rupsha and Bhairab, with the tributary Mayur river as the primary source for irrigation for peri-urban farmers. Reliance on the Mayur river is significant, especially during the dry period (November–April) (Fig. 1). To evaluate the prevailing water quality, samples were collected from 20 sampling points localized in different surface water bodies in and around the city in winter (November to February), summer (March to June) and monsoon (July to October) seasons. Sampling points cover the various sources of irrigation, such as rivers, canals/drains, lakes and ponds (*supplementary materials: Table 1*). Canals and drains receive domestic wastewater directly from households and discharge to the surrounding rivers. Small lakes and urban ponds (too small to be made visible in Fig. 1) are used by a small part of the population for bathing, washing and fishing and generally do not connect with the rivers or canals, except in case of floods. Sampling points were selected with regards to the land use pattern of the city. For example, the eastern part of the city accommodates several small and medium-sized industries and thus, samples from the east were primarily selected for heavy metal analysis. Similarly, samples for microbial analysis were collected mainly from the western part, especially from the areas where farmers were extracting irrigation water. Sample collection for winter, summer and monsoon seasons occurred respectively in January, April and August 2018. 40 samples (20 for microbial and 20 for heavy metal analysis) were collected in each season.

2.2. Water quality assessment in laboratory and statistical analysis

Microbial assessment samples were collected in sterilized glass bottles to estimate the concentrations of Total coliform (TC), Faecal coliform (FC), *E. coli* and *Enterococcus* using the standard Membrane Filtration (MF) method number 9222 and 9230 as explained in literature (APHA/AWWA/WEF, 2012). Membrane filters (0.45 μm pore size, Sartorius RC White-sterile brand) were used to filter the samples that were used to inoculate agar plates in various dilution series. The plates were prepared from different agar media. After inoculation, petri dishes were incubated (35 °C for 24 h for TC, 44 °C for 24 h for FC, 44.5 °C for 24 h for *E. coli*, 35 °C for 48 h for *Enterococcus*). After incubation, the colonies formed were counted and back-calculated in colony-forming units per 100 ml (cfu/100 ml). Following the analysis, arithmetic mean was used to express the average number of microorganisms in water which was recommended in the literature (APHA/AWWA/WEF, 2012; Haas, 1996). Relevant and necessary chemical-physical water quality information was used based on the previous study carried out in the same sampling locations of the study area (Haldar et al., 2020).

The samples were collected in standard PPT bottles and transported to the laboratory to determine heavy metal contamination. First, the samples were filtered with filter paper (Whatman No. 41) and 1 ml HNO_3 (65%) per 100 ml was added to the samples to reduce the pH level for preservation. Second, the samples were homogenized and directly measured with the ICP-OES AVIO 500 machine from PerkinElmer. The presence of aluminum (Al), arsenic (As), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), nickel (Ni), titanium (Ti) and zinc (Zn) in the water samples were conducted following the standard method number 3120 (APHA/AWWA/WEF, 2012). The arithmetic mean was used to express the average heavy metal concentration in collected water samples. MS Excel and IBM SPSS 25.0 were used to perform necessary statistical analysis (e.g. descriptive statistics, ANOVA, correlation analysis) at 95% confidence interval and produce graphical illustrations such as graphs and scatter plots. ArcGIS 10.6 was used to generate maps based on the spatial information of the study area collected from the local municipal agencies.

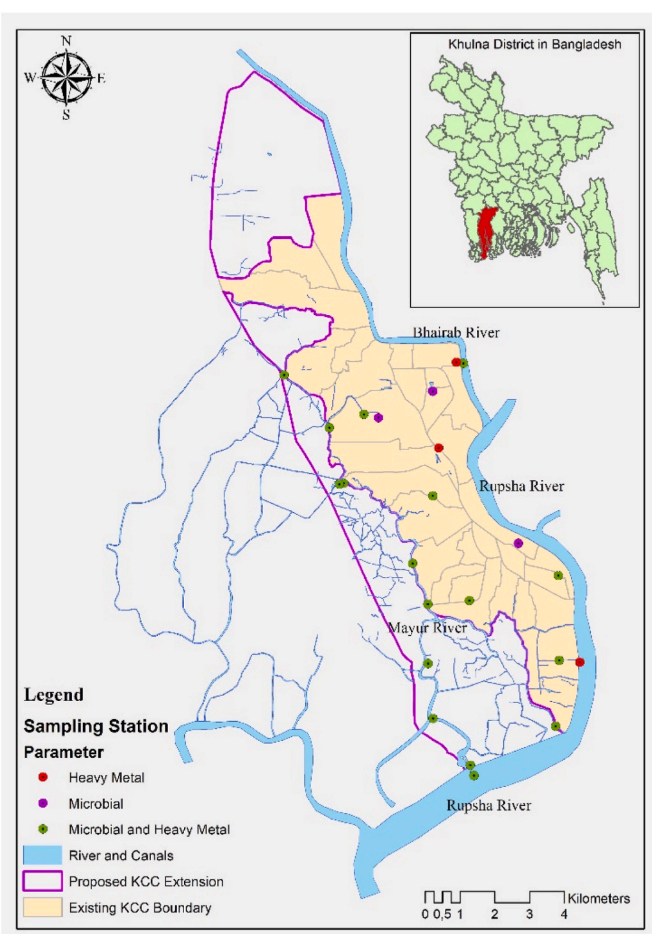

Fig. 1. Locations for collecting water samples.

2.3. Farmer's survey for perception analysis

A structured questionnaire was developed, pre-tested and deployed to understand health-related issues of the farmers who use surface water for irrigation. In total, 38 peri-urban farmers were surveyed in 2018 (Demographic information of the surveyed farmers can be found in *supplementary materials: Table 2*). The questionnaire included questions on crop health and yield, irrigation and fertilizer practices, perception towards water quality, experienced health-related problems, use of protective equipment during irrigation practices and risk perception. In addition, farmers were asked to rate their risk perception on various issues related to current irrigation practice on a scale of 1 (low-risk perception) to 5 (high-risk perception). Responses were recorded in an online-offline platform (Kobo Toolbox), including their GPS locations. Farmers were selected randomly among those whose farm was in the proximity of the Mayur river and had a higher chance of regularly exposing themselves to the water from indirect wastewater irrigation.

2.4. Quantitative Microbial Risk Assessment (QMRA)

In the early 1990s, QMRA was first proposed for water safety management (Regli et al., 1991; WHO, 2016). Since then, QMRA has been used to estimate risk levels for different water usage such as drinking water, recreational water, wastewater irrigation (WHO, 2016). In general, QMRA predicts risk based on exposure to one type of pathogen at a given time (Drechsel et al., 2010a; Haas et al., 1999). Based on the general characteristics, QMRA can have three different levels: screening, advanced and in-depth level and these levels include four steps for water-related risk assessment: hazard identification, exposure assessment, health effects assessment and risk characterization (Abrahams et al., 2004; Haas et al., 1999; WHO, 2016). Screening level QMRA provides a quick, low-cost overview of the level of risk, whereas advanced and in-depth level risk assessment offers more detailed and comprehensive information on risks but also requires higher cost and time involvement (WHO, 2016).

The selection of appropriate levels and steps of QMRA depends on the overall aim of the risk assessment (WHO, 2016). This study aimed to highlight the concerns associated with the current irrigation practice and thus, an initial screening-level risk assessment was performed using a deterministic model with point estimates of pathogen concentrations. Theoretically superior and accurate to the deterministic model is the stochastic model, which accounts for the uncertainty over model elements; however, the model is complex and requires previously obtained knowledge on probability distributions and the use of Monte Carlo simulation (Hamilton and Stagnitti, 2008). Using a simple deterministic model, on the other hand, provide insights that could be useful in identifying the potential errors in complex stochastic models (Zwietering, 2009). As the necessary knowledge on variability and uncertainty over model inputs to quantify the risks was not available, this study oriented on determining the initial screening levels of risks, using single-point pathogen concentration estimates (WHO, 2016). This is the first step in risk assessment and can be followed (not done in this study) by a more quantitative assessment, eventually delivering risk results expressed in Disability Adjusted Life Years (DALYs). However, this requires much more detailed knowledge on probabilities of infection, illness and variability and needs to be accompanied by an uncertainty analysis based on Monte Carlo modeling techniques which was beyond the scope of this study.

2.4.1. Hazard identification

Hazard identification, the first step in QMRA, was performed to define the investigation's scope and purpose and formulate specific risk problems (WHO, 2016). The study area's local context and socio-cultural aspect were considered to select the particular pathogenic indicators and the relevant exposure pathways as done in literature (Ferrer et al., 2012). Pathogenic bacteria such as *E. coli* O157:H7, *Salmonella typhimurium*, *Shigella dysenteries* and *Vibrio cholerae* in water sources are associated with the major causes of diarrheal diseases and gastrointestinal infections worldwide (Momba et al., 2006; Teklehaimanot et al., 2014). In the study area, the presence of FIB in the surface water, especially *E. coli* and *Enterococcus*, is reported in previous studies (Islam et al., 2018b; Islam and Islam, 2020). Thus, in this study, the probability of infection is modeled assuming a fraction of the total counted *E. coli* being *E. coli* O157:H7. A ratio of 1:0.08 for *E. coli*:*E. coli* O157:H7 was used based on literature (Haas et al., 1999; Machdar et al., 2013) to assume the concentration of *E. coli* O157:H7 as this specific variant could not be detected in the local laboratory. The absence of research infrastructure in developing countries has been identified as a major challenge for an in-depth QMRA (Dias et al., 2019; Islam and Islam, 2020). This study focuses on the peri-urban farmers surrounding Khulna city who are indirectly using urban wastewater for irrigation and *E. coli* was selected as the microbial parameter to simulate the potential health risk.

2.4.2. Exposure assessment

In the exposure assessment, the frequency and magnitude of exposure to pathogens through different pathways were estimated (WHO, 2016). Exposure quantitatively indicates the pathogen's dose that a host ingests, inhales, or gets in contact with and is often identified as a route from the pathogen source (e.g. water) to the actual exposure event (e.g. accidental ingestion) (Haas et al., 1999). This study focused on the oral route of accidental ingestion by farmers while working in the field. Wastewater that enters the surface water body without any treatment typically contains remnants of human excreta. Similarly, animals grazing in the surrounding areas also excrete into the environment and the microbial pollutants in part reach surface water bodies through surface runoff. Farmers pump surface water to their agricultural fields and move around the field with bare feet. They come into contact with the surface water containing pathogens or may accidently ingest the polluted irrigated water (Fig. 2).

The exposure dose (cfu) per event was calculated using the following formula:

$$\text{Dose} = C \times q \tag{i}$$

where, C is the concentration of pathogens in the surface water (cfu/ml) and q is the volume of accidental irrigation water ingestion by farmers (ml).

Studies suggest that farmer's accidental ingestion of irrigation water range from 1 to 5 ml/event and for the simulation purpose a median value of 3 ml/event was assumed for single event per day spent in the field was (Moazeni et al., 2017; Symonds et al., 2014).

2.4.3. Health effect assessment and risk characterization

The health impact data for the identified hazards and the specific study population was assessed using a dose-response model in the health impact assessment (WHO, 2016). The dose-response model is a mathematical relationship between the dose of pathogen uptake by the receptor (i.e. farmer) through various routes (e.g. direct ingestion, inhalation or contact) and the probability of response (e.g. a form of infection, illness or death) (Haas et al., 1999). In this study, ingestion was assumed to be the main route because the study indicated that farmers work in the field without any protection which increases the chance of accidental ingestion (Mojid et al., 2010). In general, two types of models are being used to assess the dose-repose relation: the exponential model and the Beta-Poisson model (WHO, 2016). The exponential model assumes that the probability of infection can be shown as a function of ingested dose and Beta-Poisson is characterized by a median infectious dose and a slope parameter (Haas et al., 1999). In this study, for pathogenic microorganisms, the Beta-Poisson model is more appropriate and thus used due to the distribution of microbes in the environment and the interaction with the target population (Ferrer et al., 2012; Haas et al., 1999).

The probability of daily infection from a specific pathogenic microorganism was calculated using the following formula:

$$P_{i(d)} = 1 - \left[1 + Dose\frac{2^{\frac{1}{\alpha}} - 1}{N_{50}}\right]^{-\alpha} \tag{ii}$$

where, $P_{i(d)}$ is the daily probability of infection from specific pathogen *i*, N_{50} is the number of pathogens infecting 50% of the exposed population and α is the kinetic parameter (constant).

The annual probability of infection was calculated using the

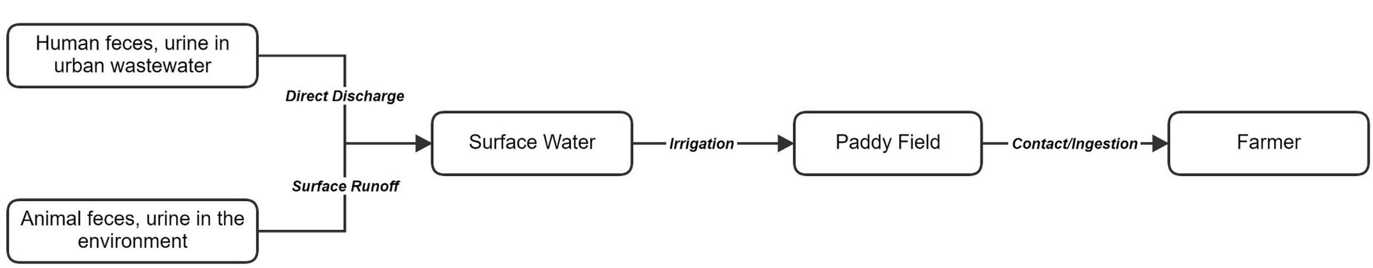

Fig. 2. The exposure route of accidental ingestion of wastewater.

following formula:

$$P_{i(A)} = 1- [1-P_{i(d)}]^n \quad \text{(iii)}$$

where, $P_{i(A)}$ is the annual probability of infection by ingesting pathogens and n is the exposed duration (days/year).

Literature indicates that farmers are exposed 50–80 days while irrigating fields, however, a default value of 75 days per year was used as exposure days for simulating the annual risk of infection (WHO, 2006). For seasonal risk of infection, the exposure days were determined based on the farmer's survey and other related information such as kinetic parameter α, a dose resulting in 50% infection, was also based on literature (Table 1). Reduction of pathogenic concentration (log_{10} removal) using technical and non-technical measures was simulated to formulate risk mitigation strategies to ensure the safe reuse of water in the study area.

3. Results and discussion

3.1. Microbial water quality

Laboratory analysis provided information on the concentration levels of TC, FC, *E. coli* and *Enterococcus* in the study area's surface water bodies (Fig. 3). The mean concentration of TC exceeded the local standards (<1000 cfu/100 ml) for inland surface water useable for irrigation for all sampling points around the year (GoB, 2002). The mean concentration of TC was the highest during the summer (1×10^6 cfu/100 ml) and lowest in the winter (8×10^5 cfu/100 ml). Similarly, the mean concentration of FC (in cfu/100 ml) was high during the summer and monsoon seasons ($4 \times 10^5$and 5×10^5 respectively) as compared to the winter (7×10^4). The mean *E. coli* concentration (in cfu/100 ml) was lower during the winter (4×10^4) than in summer and monsoon i.e., 3×10^5 and 4×10^5, respectively (*supplementary materials: Tables 3 and 4*). Several previous studies also indicated the elevated level of FC and *E. coli* during summer and monsoon in other areas of Bangladesh (Islam et al., 2011, 2017; Kostyla et al., 2015; Zabed et al., 2014). However, the concentration of enterococcus was lower during summer (7×10^3 cfu/100 ml) than in the monsoon season (2×10^4 cfu/100 ml). The presence of light accelerates *enterococcus*'s decay, which may have been linked with the lower concentration during summer compared to the monsoon season (Bordalo et al., 2002).

Correlation analysis indicates that water temperature had a significantly positive influence on the FC ($P < 0.01$) and *E. coli* ($P < 0.05$) concentrations. Similarly, a positive correlation between water temperature and TC was found but not statistically significant (*supplementary materials: Table 6*). The climatic data in the last two decades indicated that the region had an average maximum atmospheric temperature between 32 °C and 36 °C from April to October and the warm climate may have favored the growth of FC and *E. coli* resulting in higher concentrations (Barcina et al., 1986; Dey et al., 2017; Haque et al., 2019; Islam et al., 2017; Jang et al., 2017; Vermeulen and Hofstra, 2014). Similarly, ANOVA indicates the significant seasonal variation ($P < 0.05$) in FC, *E. coli* and *Enterococcus* concentrations except for TC. Heavy rainfall contributes to the higher dilution and excessive runoff during the monsoon season from nearby built-up areas where septic tanks, domestic animal sheds and wet markets are more common. The variation was highest during monsoon for all microbial indicators, which is most likely related to heterogeneous contributions of pollution sources and dilution by run-off waters. The presence of grazing cattle, wet markets, runoff from septic tanks and the dumping of untreated wastewater all most likely contribute to the high and varying concentrations of FIB in the surface waters also found by other authors (Ekklesia et al., 2015; Falardeau et al., 2017; Islam et al., 2018b; Jang and Liang, 2018; Myers and Kane, 2011; Ramos et al., 2006).

The standard deviation of pathogen concentrations indicates the very high concentration variability among sources, further validated using statistical analysis. ANOVA shows the significant ($P < 0.05$) spatial variation in TC, FC, *E. coli* concentrations among different sources in the study area (*supplementary materials: Table 5*). The overall mean concentration of TC for canal/drains was 2×10^6 cfu/100 ml, whereas for the river, the concentration was 8×10^5 cfu/100 ml and the concentration was highest during summer. The canals and drains occasionally receive effluents from the septic tanks via leakage or illegal dumping, whereas wastewater or runoff gets diluted with the river water and the tidal effect contributes to the movement of water, which may have an impact on the variability of the concentration over different sources.

FC and *E. coli* concentrations in all the sampling stations also exceeded the WHO guideline (≤1000 cfu/100 ml) for unrestricted use in agriculture, except for an urban pond owned by the local municipal authority. The pond is not open for regular activities and is occasionally treated with bleaching powder. The application of chlorinated lime or bleaching powder (calcium hypochlorite) can reduce (around 60%) the faecal contamination in water sources (Roy et al., 2016; Sirajul Islam et al., 2007). Two other urban ponds that were not under the municipal authority were used extensively by the local population for domestic activities, such as bathing and washing and had several folds higher TC and FC concentrations than the WHO threshold. Bathing in such microbially polluted waterbodies could lead to severe illness and increase infection chances, especially among children (Islam and Islam, 2020). Overall, the pathogen concentrations exceed the current national and international guidelines for using surface water for irrigation and daily activities, thus posing a health risk for the user groups.

3.2. Risk perception of farmers

Farmer survey indicated that most farmers (95%) have been using surface water sources, especially the Mayur river and nearby canals, as their primary source of irrigation for decades. Most of them (63%) understand their irrigation source regularly receives domestic wastewater from adjacent urban areas and mentioned the reliance on the existing sources due to lack of alternatives. Most farmers (84%) do not use any protective equipment during irrigation, thus enhancing the chance of accidental ingestion. Lack of protective equipment could lead to a higher risk of infection for farmers and their family members (Keraita et al., 2008; Mojid et al., 2010). In addition to accidental ingestion, peri-urban farmers also face other obstacles daily. More than 45% of the farmer

Table 1
Values used for QMRA simulation.

Parameter	Unit	*E. coli* O157:H7	Reference
Mean concentration (C)	cfu/ml	Winter: 2.8×10^3 Summer: 2.6×10^4 Monsoon: 3.3×10^4 Overall: 2×10^4	(Haas et al., 1999; Machdar et al., 2013) and this study
Kinetic parameter (α)	–	0.49	(Amha et al., 2015; Gibney et al., 2014; Haas et al., 1999, 2000)
Dose resulting 50% infection (N_{50})	–	5.96×10^5	
Volume of ingestion (q)	ml	1-5; Median: 3	(Moazeni et al., 2017; Symonds et al., 2014)
Exposed days (n)	days/year	50-80 (WHO default value 75)	(Moazeni et al., 2017; Symonds et al., 2014; WHO, 2006)
	days/season	22	This study

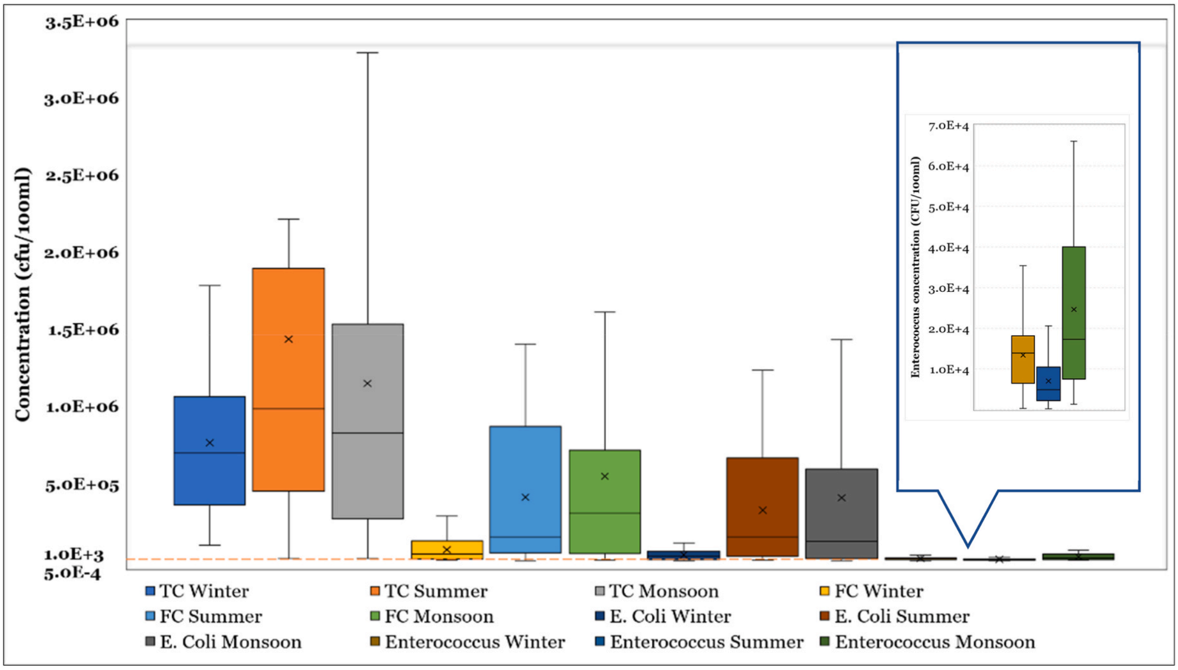

Fig. 3. Concentrations of TC, FC, *E. coli* and Enterococcus in the surface water (red dotted line indicates the allowable threshold for coliforms in WHO and local standards). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

reported odor, skin irritation, skin blistering and water-borne diseases like diarrhea after working in the field during irrigation which was also reported in previous studies (Haldar et al., 2021; Mojid et al., 2010). However, farmers' risk perception towards their current practice indicates that the peri-urban farmers rank health-related issues lower in the list compared to other issues (Fig. 4).

Farmers rank excessive presence of weeds and pests, which grow due to indirect wastewater irrigation in the field, as a top risk, followed by crop health. Their own health comes third in the list, followed by soil health and the local environment. Prioritizing farming-related issues over health issues is also observed in previous studies and farmers accepted those health risks considering the lack of available irrigation sources and potential economic gains of wastewater use (Adjaye-Gbewonyo, 2008; Drechsel et al., 2010a; Weldesilassie et al., 2011). Studies also indicated that experience in working with wastewater, education level, source of information, socio-economic condition influence the health risk perception among farmers (Drechsel et al., 2010a; Keraita et al., 2008; Obuobie et al., 2006; Weldesilassie et al., 2011). Similarly, in the study area, farmers who have been farming for more than 20 years did not perceive health risk as a major concern. Damage to the pump is the lowest on the list as the pumps are easily repairable and required materials are locally available. As excessive weed growth is common in the study area, farmers use chemical fertilizer to increase the crop yield and control weed growth and pest control in the field.

A very small number of farmers (16%) use a piece of cloth to cover their face during field activities, but that is not sufficient to protect them against the polluted surface water. The survey also revealed that the usability of the protective equipment, lack of information about the usefulness of protective equipment along with the high cost are the primary reasons for not using necessary protections during field work which is generally mentioned in other global studies (Lamnisos et al., 2013; Mayilla et al., 2016; Obuobie et al., 2006). Using necessary

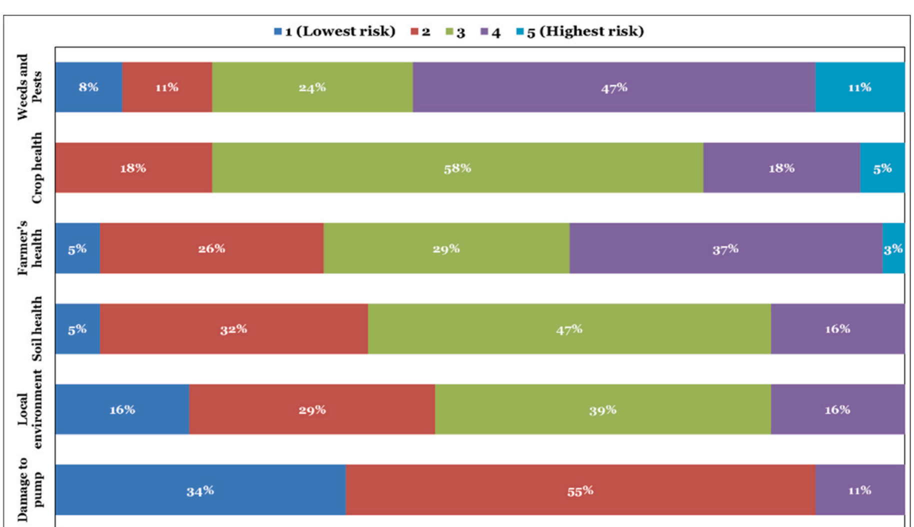

Fig. 4. Risk perception of farmers of their current irrigation practice.

protective equipment during farming activities is a low priority for their health due to their long-standing irrigation practices without any protection when the water used to be comparatively clean (Mayilla et al., 2016). Farmers also mentioned that they face difficulty in farming activities while wearing protective equipment such as boots or gloves, making it difficult to move and work in the muddy paddy field. However, this should not be a reason for failing to protect farmer's health as this equipment could easily be used for other farming activities such as vegetable or fruit farming. Farmers also mentioned taking basic medicines from local pharmacies and home remedies when they get sick after contacting polluted surface water.

3.3. Potential microbial health risks for farmers

The relation between the pathogen concentration and farmer's health risk due to accidental ingestion was simulated through the QMRA model and it indicates seasonal infection probabilities also risk of infection based on various irrigation water sources (Table 2). The daily probability of infection is higher in summer and monsoon (2×10^{-3}) compared to winter season (2×10^{-4}). The overall daily probability of infection for a single event is three orders of magnitude higher compared to the recommended limit of $<10^{-6}$ by WHO; similar to other studies from other parts of the world (Amha et al., 2015; Kouamé et al., 2017; Signor and Ashbolt, 2009; WHO, 2016). The infection probability also varies over the sources used for irrigation. The overall daily probability of infection is high for canal/drain (3×10^{-3}) followed by the river (8×10^{-4}) and lake/pond (5×10^{-5}) samples. This variation is understandable due to the variable *E. coli* concentrations across different sources; rivers and drains have a higher concentration than lakes and ponds.

Considering the 22 seasonal exposure days, the annual probability of infection in winter is the lowest (0.004), whereas the summer (0.04) and monsoon (0.05) have the highest probability (Fig. 5). However, the annual risk of infection is still much higher than the WHO guideline ($<10^{-4}$) for an acceptable risk limit (Amha et al., 2015; Signor and Ashbolt, 2009; WHO, 2016). Similar to values for the daily probability of infection based on sources, the annual risk of infection (considering WHO default 75 exposure days) is also high for river and canal/drain samples compared to the pond/lake samples. The overall annual risk of infection is highest (0.2) for canal/drain samples, followed by the river (0.06) and lake/pond (0.003) samples. Considering all samples, the overall annual risk of infection is 0.1 which is three orders of magnitude above the acceptable limit. The *E. coli* concentration was significantly different over sources, thus resulting in a higher annual risk of infection probability for canal/drain than lakes.

Farmers only rely on external irrigation during the dry period, i.e. the whole winter and parts of the summer season; thus, the calculated risks of infection for the monsoon season may not correspond to the practical situation of the farming practices of the past years. However, changes in the climatic variability in the Bengal delta will result in greater unpredictability of rainfall and droughts, which might force farmer's reliance on surface water throughout the year in the future (Gain et al., 2014; Kumar et al., 2020; Rahman et al., 2011). In addition to that, assuming the counted fractions of *E. coli* to be all *E. coli* O157:H7, one of the most infectious pathogenic E Coli variants, may result in overestimated values for infection probabilities has been indicated by others (WHO, 2016). However, additional simulations considering 0.01%, 0.05%, 0.1%, 0.5%, 1%, 2%, 5% and 10% of the initial concentrations being *E. coli* O157:H7 also resulted in daily and annual probability of infection above the WHO acceptable limit and the probability of infection start to decrease around 0.01% (*supplementary materials: Table 7*). Considering 10% of the counted *E. coli* concentrations to be this pathogenic variant, the overall annual risk of infection was 0.14, whereas for 0.1% of the annual risk of infection was 0.0002, which is still above the WHO acceptable limit.

Table 2
Daily probability of infection due to current practice.

Source	Winter	Summer	Monsoon	Overall
All Samples	2×10^{-4}	2×10^{-3}	2×10^{-3}	2×10^{-3}
River	2×10^{-4}	1×10^{-3}	1×10^{-3}	8×10^{-4}
Canal/Drain	4×10^{-4}	4×10^{-3}	5×10^{-3}	3×10^{-3}
Pond/Lake	1×10^{-5}	6×10^{-5}	7×10^{-5}	5×10^{-5}

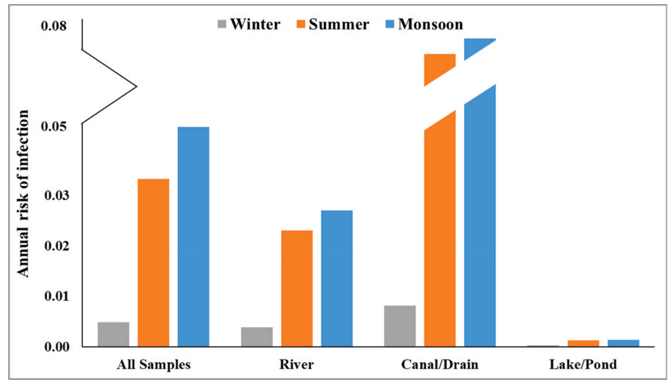

Fig. 5. Annual risk of infection over different sources for *E. coli*

The survey among the local farmers who has been using polluted surface water as irrigation water revealed that more than 26% of the farmers suffered from water-borne diseases after working in the field. We calculated an overall infection probability between 2 and 10% and only for pathogenic *E. coli*, so the actual observed infection risk from the survey is higher than this QMRA assessed value. This is logical since microbial indicators, such as *E. coli* and Salmonella (data not shown), were also present in these waters and others (viruses, protozoa, helminth eggs) can also be expected to be present; hence, an accumulative risk of multiple pathogens can be expected. Moreover, the actual infection rate in real-world situation may differ from the theoretical QMRA based risk assessment as infectivity varies between individuals based on the immune system, age and other health factors (WHO, 2016). The input model parameters of QMRA are often derived based on studies conducted in developed countries, raising the debate on the applicability of QMRA for developing countries (Mills et al., 2020). It is often generalized that people from developing countries have a stronger immune response system for water-related pathogens compared to their counterparts, though the opposite could also be easily reasoned. Thus, further investigation is necessary to estimate the actual risk in the context of the study area. The insights from this study on the seasonal probability of risk of infection were used to highlighting the current risk to take necessary strategies to mitigate the risks.

3.4. Risk mitigation for safe irrigation practice

The analysis has indicated that the concentrations of selected pathogenic microbial indicators in the surface water are exceeding the national and international guidelines for use, leading to an increased annual risk of infection. A multiple-barrier approach containing a series of technical and non-technical measures could reduce the current risk for the farmers (Drechsel et al., 2010b; Fuhrimann et al., 2016; Janeiro et al., 2020; Keraita et al., 2008). As the current irrigation sources receive a regular municipal discharge, a treatment system followed by necessary disinfection would remove $\log_{10}$ 3 of the prevailing concentrations of *E. coli* lowering it to the safe limits (Sperling et al., 2005). Implementation of technical strategies alone usually cannot reduce the health risk below the acceptable limit by only reducing the accidental ingestion volumes (*supplementary materials: Table 8*). Reducing pathogen concentration by treating wastewater before discharge as a technical strategy and reducing accidental ingestion to the minimum (1 ml/event)

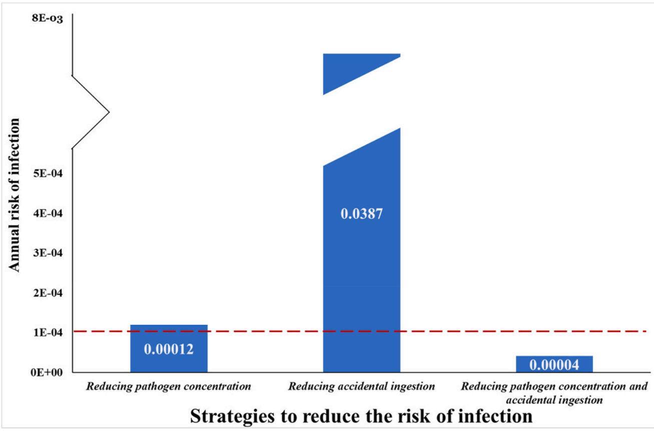

Fig. 6. Health risk after implementing technical and non-technical strategies (red dotted line indicates the acceptable health risk limit). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

using protective equipment and raising awareness and education programs as non-technical strategies, could significantly lower the health risk within the acceptable limit (Fig. 6). The authority should regularly monitor the water quality and enforce the necessary rules and regulations to prevent untreated discharge. The outflows from the septic tanks should be managed and de-sludged to prevent partially treated black water overflow into the surface water bodies as poorly managed system increases the chances of health risks (Foster et al., 2021). The sludge from the septic tanks could be further processed using appropriate technology suited to the local context (Drechsel et al., 2015; Fuhrimann et al., 2016; Hanjra et al., 2012; Tilley, 2014).

Farmers should be encouraged to use protective equipment, where possible, to reduce the incidents related to accidental ingestion. Only reducing the accidental ingestion to a minimum (1 ml/event) will be insufficient to reduce the health risk if the concentration remains high (*supplementary materials: Table 8*). Additionally, access to necessary health treatment (for severe illness), regular health awareness, an education program for farmers and their family members is crucial to reducing health risks (Utzinger et al., 2009). The agricultural extension agency could ensure access to protective equipment or education programs through government subsidies or grants, especially for economically marginalized farming groups. Combining technical and non-technical strategies would lead to reduced pathogen concentration in surface water sources and decreased chances of accidental ingestion, bringing the annual risk within the acceptable limit. Strategies should also include other stakeholder groups in the food chain i.e, market vendors and consumers as they also suffer from indirect wastewater irrigation (Barker et al., 2013; Ferrer et al., 2012). Awareness and information campaigns are necessary to prevent cross-contamination at the market level and increase safe storage and processing at the household level (Drechsel et al., 2010a; Fuhrimann et al., 2016; Tram et al., 2008). A strong monitoring and warning system for microbial contamination can help early detection take necessary measures to protect farmers' health (Fuhrimann et al., 2015; WHO, 2006).

3.5. Heavy and other metal contamination in surface water

Heavy metal analysis indicates that only Al, Fe, Mn, Ti and Zn were detected in the surface water and all, except Mn, had significant ($P < 0.05$) seasonal variations. However, all measured concentrations were below the FAO recommended limit for agricultural use (Table 3). The Mn concentration in surface water was near the FAO maximum allowable limit for safe irrigation (0.2 mg/L). Prevailing sources such as untreated dumping of wastewater could lead to the presence of manganese in the surface water (Metcalf & Eddy, 2013). The coastal districts of Bangladesh have manganese (Mn) concentrations beyond the national (BDS) and international (WHO) drinking water guidelines, which could also contribute to the Mn concertation in surface water (Rahman et al., 2021). Fe's concentration increases five-fold (from 0.26 mg/L to 1.37 mg/L) during monsoon compared to winter and Al concentration increases drastically (from 0.12 mg/L in winter to 1.41 mg/L in monsoon) due to the excessive runoff during that period (Bhardwaj et al., 2017; Measures et al., 2005).

The concentration of As, Co, Ni, Cd, Cr, Cu and Pb in the collected water samples was below the detection limits, which can be explained by the declining presence of traditional heavy mills and industries (jute, garments, cable) in the area (Rahman and Kabir, 2019) and prevalence of manufacturing SME's in categories like agro-processing, bakery, light engineering, timber and furniture. Several studies from the other parts of the country where heavy industrial zones (textiles, agro-chemical, dye, paint and ceramics) are dominant, the concentrations of heavy metals in water, soil and the crops (vegetables) were above the national and international standards (Ahmad and Goni, 2010; Ahmed et al., 2018, 2019). Two apparent reasons could cause a bit deviating situation in the study area i) a relatively low contribution of SMEs and other enterprises to water pollution or removing pollutants from the surface water resources. In addition to that, during the field survey, the excessive presence of water hyacinths - a fast-growing, free-flowing weed was observed in surface water bodies (*supplementary materials: Fig. 1*). Water hyacinth can absorb and remove heavy metals from wastewater through the roots (Ingole and Bhole, 2003; Muramoto and Oki, 1983; Rezania et al., 2015; Zheng et al., 2016). For example, studies show that water hyacinth removed almost 65% of Cr and Cu from wastewater simulated in a wetland-based system (Lissy and Madhu, 2011).

Table 3
Heavy metal concentration in the surface water of Khulna.

Parameters (mg/L)[a]	Season (N = 20) (Mean ± SD)			FAO Recommendation Limit (mg/L)	Detection Limit (mg/L)
	Winter	Summer	Monsoon		
Aluminium (Al)	0.12 ± 0.09	0.57 ± 1.09	1.41 ± 1.81	5	0.1
Iron (Fe)	0.26 ± 0.23	0.62 ± 1.14	1.37 ± 1.41	5	0.1
Manganese (Mn)	0.26 ± 0.37	0.18 ± 0.25	0.21 ± 0.25	0.2	0.01
Titanium (Ti)	0.05 ± 0	0.06 ± 0.04	0.09 ± 0.06	N/A	0.01
Zinc (Zn)	0.67 ± 1.23	0.1 ± 0.03	0.16 ± 0.27	2	0.1
Arsenic (As)				0.1	0.1
Cobalt (Co)				0.05	0.1
Nickel (Ni)				0.2	0.1
Cadmium (Cd)		Below the detection level		0.01	0.01
Chromium (Cr)				0.1	0.01
Copper (Cu)				0.2	0.01
Lead (Pb)				5	0.01

[a] Bold-italic parameter indicates the significant ($P < 0.05$) temporal variations.

Similarly, in artificial lake water Cu, Pb, Cd and Zn concentration decreased 24%, 26%, 50% and 57%, respectively, after 8 days of experiment with water hyacinths (Smolyakov, 2012). A similar process might have taken up a portion of heavy metals by the roots of water hyacinths from the surface water bodies, resulting in heavy metal concentrations below detection level. Another reason for the lower concentrations of heavy metals in surface water could be the deposition of heavy metal minerals in the riverbank soils and sediment, giving a delayed emission to the water phase due to sorption processes. Studies indicate that the riverbank soil can absorb heavy metals in large quantities of heavy metals even when repeatedly exposed to highly polluted mineral or effluent disposals (Chang et al., 1984; Kumar Kumar Sharma et al., 2007; Li et al., 2015; Yang et al., 2018). However, at some point, adsorption saturation would occur and higher emissions levels can then be expected. As the surface water bodies and riverbanks receive wastewater and mineral disposals for decades, the deposition of heavy metals in the riverbank soils and river sediments requires further investigation.

3.6. Limitations of the study and future research scope

This study has indicated a potential health risk related to current practice, but an in-depth level study would provide a more comprehensive understanding of the health risks, which would be useful in adopting required risk mitigation strategies. Future assessment considering the human enteric pathogens should include at least one virus, one bacteria, one protozoan, or even the presence of helminth eggs to understand the range of behaviors in pathogen groups to formulate specific risk mitigation strategies (WHO, 2016). Additionally, a study on plant uptake and deposition in the soil could provide further insights into the study area's heavy metal contamination. Currently, the surface water is deemed safe in terms of heavy metal contamination for agricultural use. However, increasing industrial activities may threaten the chemical health risk for farmers and consumers. Future studies should focus on quantifying the potential chemical risks to formulate risk mitigation strategies. The city is expected to have growing economic activities in the coming period, which may increase the presence of heavy metals in the surface water if not treated (ADB, 2020).

4. Conclusion

This study aimed to assess the risks related to indirect wastewater irrigation among peri-urban farmers based on a questionnaire survey among farmers and a determination of the microbial quality of surface water resources around the Bengal delta city of Khulna. In the survey, 26% of the farmers indicated water-borne-related health effects in the survey. Further, the results of the survey found that farmers rank excessive weed growth, nuisance of pest and crop health as the most important concerns, even above their own health. This seems to be related to their longstanding working experience with polluted surface water. The results found in this study for the city of Khulna indicate that surface water used for peri-urban agriculture has no significant concentrations of heavy metals, but does have very poor microbial quality. Further, when compared to national and international guidelines, the pathogen levels are several magnitudes too high. This pollution is linked to the direct discharge of domestic wastewater and the associated anthropogenic activities which excessively affecting surface water quality. Taking *E. coli* concentrations in surface water and the variations herein as the basis for a QMRA risk assessment, noteworthy health threats to farmers were identified (3–4 magnitudes too high compared to WHO limits), especially during the monsoon and summer seasons. Various measures were considered in mitigating these risks, including an education program for the farmers to protect their health and protective equipment for farmers while irrigating with polluted surface water. However, the most effective measure is the treatment of the urban water-reducing the pathogen levels in surface water within the recommended limit. Overall, the surface water quality needs to be improved by preventing the direct discharge of wastewater as well as applying adequate treatment. It is recommended that all stakeholder groups should be informed to ensure safe irrigation practices. This research showed possible health outcomes for farmers due to *E. coli* infections. An in-depth QMRA considering other microorganisms, such as bacteria, viruses, protozoa and helminth eggs, would provide a comprehensive image of the risks associated with indirect wastewater irrigation. Moreover, chemical pollution such as organic micropollutants, in addition to the heavy and other metals studied here, could further complete the picture of risks and treatment measures needed. Consumers and market vendors should also be considered in a complete risk assessment and strategies to reduce the risk of infection and chemical pollution. Implementation of technical and non-technical measures are needed to ensure safe water reuse for farming activities, which is crucial for sustaining agricultural production in this part of the Bengal delta.

CRediT authorship contribution statement

KH: Conceptualization, Methodology, Data Collection, Curation and Analysis, Writing the original draft. KKR, NH, DKD and HR: Conceptualization, Methodology, Supervision, Manuscript review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijheh.2022.114002.

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