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Research paper

Replacing conventional surface irrigation with micro-irrigation in vegetables can alleviate arsenic toxicity and improve water productivity

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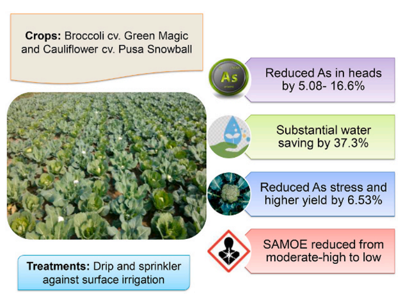
HIGHLIGHTS

- Micro-irrigation reduced As in broccoli (6.78–15.6%) and cauliflower (5.08–16.6%).
- Increased head yield, weight and diameter of broccoli and cauliflower.
- Substantial water was saved under drip and sprinkler irrigation (upto 37.3%).
- Reduction in As reduced plant stress and antioxidant enzyme activity.
- Dietary carcinogenic risk estimates was reduced considerably.

GRAPHICAL ABSTRACT



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ABSTRACT

Arsenic (As), a heavy metal(loid), is exceedingly hazardous and carcinogenic and harms people, soil, plants, and water. Vegetable consumption can be a source for the absorption of As in humans. To find a feasible mitigation technique, a field experiment was conducted with broccoli (cv. Green Magic) and cauliflower (cv. Pusa Snowball) in geogenically arsenic-contaminated areas (West Bengal, India) for two consecutive years in a randomized block design replicated seven times with surface irrigation of 20 mm depth, gravity drip and sprinkler irrigation at 1.0 and 0.7 of pan evaporation replenishment. Results revealed that the lowest As accumulation in the edible heads was accomplished by micro-irrigation (0.34 and 0.31 mg kg^{-1}) over the farmer's practice of surface irrigation (0.42 and 0.38 mg kg^{-1}) for broccoli and cauliflower. Micro-irrigation improved the average head yield by 5.26 and 6.53%, weight by 6.37 and 3.06%, and diameter by 1.14 and 1.23% for broccoli and cauliflower respectively and also resulted in substantial water saving to an extent of 37.3%. Further reduction in As stress reduced the activity of antioxidant enzymes like catalase, superoxide dismutase and peroxidase; and reduced the dietary carcinogenic risk like Severity Adjusted Margin of Exposure (SAMOE) from moderate-high to low. Accordingly,

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drip irrigation without water stress can benefit vegetable growing in the As-contaminated regions based on the competitive advantage.

1. Introduction

Arsenic (As) is a major soil and water contaminant in many nations due to its toxic, widespread metalloid nature (Bhattacharyya and Sengupta 2020). Its capacity to cause cancer together with long-lasting hazardous persistence has become a global issue (Laha et al., 2021; Shakoor et al., 2019). The threat of As contamination through ingested food and water with a significant proportion of As transfer along the soil-crop-food chain has already been identified. While As contamination in drinking water has been the main concern (Sengupta et al., 2022a), the transfer of As from the soil to the plant's edible part creates a nutritional conundrum and increases the risk to human health (Mandal et al., 2021; Sengupta et al., 2021). Arsenic toxicity mechanisms in the living organisms include the generation of reactive oxygen species, the substitution of necessary components in the molecular structures of proteins and enzymes, the blockage of functional groups and ultimately results in severe oxidative stress, cancer, and species extinction. This is comparable to other heavy metals and the toxicity mechanisms that go along with them (Engwa et al., 2019; Fu and Xi 2020).

Natural arsenic contamination of groundwater resources is posing a serious threat to the health of millions of people (Mandal et al., 2021) in different parts of the world with the maximum magnitude in Bangladesh followed by West Bengal, India (Laha et al., 2021). The primary cropping cycle in the Bengal Delta, which includes most of Bangladesh and the Indian state of West Bengal, is rice-rice. Farmers tend to grow rice under irrigated conditions during the post-winter season for the low cost of irrigation water and the 55–80% higher grain production compared to the rainy season (Sarkar et al., 2012). In some areas, huge amounts of groundwater are used indiscriminately to plant vegetables in addition to rice. It is well recognised that vegetables play a significant role in the nutrition of humans, serving as key sources of several vitamins, dietary fibres, and minerals like pyridoxine and folic acid (Poddar et al., 2022). The Chakdah block in Nadia district, where the current study was conducted, has been a major vegetable Agri Export Zone (AEZ), suffered a significant setback because of high As in the marketable commodity often frequently above the export threshold requirements (Das et al., 2016). It is also impossible to dispute the findings of numerous studies regarding high As accumulation in frequently consumed vegetables in the contaminated area (Bhattacharyya et al., 2021; Biswas et al., 2012; Meharg and Rahman 2003).

In the Gangetic West Bengal delta, various cultivation practices for vegetables have been employed to ensure a steady supply of crops. These practices encompass traditional methods such as floodwater irrigation, as well as modern techniques like drip irrigation. Floodwater irrigation utilized the advantage of the region's abundant water resources, allowing farmers to inundate their fields periodically. However, modernizing practices like adopting drip irrigation systems, which efficiently deliver water directly to plant roots, reduce water wastage and enhance crop productivity (Bhattacharyya et al., 2021; Patra and Sengupta 2022). Additionally, practices like intercropping and crop rotation are used to optimize land use and enhance soil fertility.

The development of heavy metal toxicity in plants occurs in a number of ways, among them the chief being the disruption of a plant's capacity to mitigate oxidative damage, accomplished *via* non-enzymatic and enzymatic mechanisms that control intracellular levels of reactive oxygen species (ROS) (Apel and Hirt 2004). Numerous antioxidant mechanisms in plants can shield them from oxidative damage (Sinha et al., 2009). Enzymatic scavengers of activated oxygen such as superoxide dismutase (SOD), peroxidase (GPX), and catalase (CAT), eliminate ROS such as $O_2^{-}\cdot$, H_2O_2, $\cdot OH$, and $\cdot O_2$, make up these defence mechanisms (Andre et al., 2010). Typically, the antioxidant system in plants keeps the generation and removal of ROS in a dynamic equilibrium. However, this equilibrium is susceptible to unfavourable circumstances that reduce the system's capacity to eliminate ROS (Du et al., 2017).

Throughout the world, cauliflower (*Brassica oleracea* var. *bortrytis*) is a significant winter vegetable crop used as a processed product or eaten fresh as a salad or cooked as a vegetable. Nadia district in the state of West Bengal is the second-leading producing district and accounts for 16% of the total growing area of the state and has the highest productivity (28.10%). With 36% of global production, India is second to China in terms of the production of broccoli and cauliflower (Bhattacharyya et al., 2022). The cauliflower growers in India are rapidly switching to the production of broccoli (*Brassica oleracea* var. *italica*) as they see the enormous potential of the domestic and international markets for this vegetable. It is well-known for its nutritional benefits due to its abundance in minerals including Ca, Mn, Fe, Mg, Se, Zn, and P, as well as vitamins A, B, B_2, and C (Kumar and Imtiyaz 2007). Beta-carotene, indoles, and isothiocyanate, secondary plant active compounds that lessen the risk of carcinogens are also present in broccoli. For the past ten years, broccoli consumption has been rising significantly, and a lot of attention has been paid to its health benefits (Erdem et al., 2010).

Surface irrigation is most commonly used for vegetable cultivation. In most of the cases, As-contaminated groundwater is used by a gravity-fed, overland flow of water. Over the years several studies have revealed that this method results in the wastage of water and reduces water use efficiency. In this regard, by lowering soil evaporation and drainage losses, generating and maintaining soil moisture conditions that are favourable for crop growth, and minimising soil evaporation, micro-irrigation techniques like drip and sprinkler can be utilized to increase irrigation efficiency (Patra and Sengupta 2022). In spite of all these promising aspects still there are very limited literatures available on how micro-irrigation can solve the problem of As toxicity in soil-plant system, which further emphasizes the novelty of this study. In light of this, the current study has been designed to determine (i) whether the use of micro-irrigation in the form of drip and sprinkler can be a solution to reduce As accumulation in vegetable crops like broccoli and cauliflower (ii) whether micro-irrigation improves crop yield and water productivity by eliminating ROS mediated stress and (iii) how far the edible parts are safe for human consumption.

2. Materials and methods

2.1. Site features and experimental details

The experiment location was chosen in the As-contaminated village of Ghentugachi in the Chakdah block of Nadia, West Bengal, India (23°02′N, 88°34′E). According to the Village Summary of Tube-well Test Results under Joint Plan of Action (JPOA) for arsenic mitigation led by Public Health Engineering Department (PHED) of the Govt. of West Bengal and United Nations International Children's Emergency Fund (UNICEF), the location was chosen due to the high As concentration of the groundwater utilized for irrigation (Sengupta et al., 2023). The research area experiences sub-tropical weather, with average annual rainfall ranging from 1200 to 1500 mm, relative humidity ranging from 36 to 85%, and maximum and minimum temperatures, respectively, of about 37.5 °C and 12 °C. The soil is a new alluvial (*Inceptisol*), described as having neutral soil pH, silty clay, a moderate amount of available N and K, and a high amount of available P. Elevated concentrations of As have been found in soil and water, particularly in shallow tube well (STW) water (Bhattacharyya et al., 2021; Das et al., 2016).

The experiment was conducted on broccoli and cauliflower during two consecutive *rabi* (winter, November to February) seasons of 2018-19 and 2019-20 laid out in a Randomized Block Design (RBD) replicated seven times with surface irrigation of 20 mm depth, gravity drip irrigation at 1.0 and 0.7 of pan evaporation replenishment and sprinkler irrigation at 1.0 and 0.7 of pan evaporation replenishment. The experimental design remained the same throughout the field trial's two consecutive years on the same plot of land.

2.2. Agronomic manipulations

The experiment location was chosen so that there is no possibility of water stagnation. In each of the two experimental years (2018–19 and 2019–20), the broccoli seed cv. Green Magic and the cauliflower seed cv. Pusa Snowball were sown in the middle of October, and 30-day-old seedlings were transplanted in the middle of November at a spacing of 60 cm (row to row) × 40 cm (plant to plant). The total plot area was 5 m × 4 m, with a 1.0 m wide buffer strip enclosing each plot to prevent seepage of water between them. The recommended dose of fertilizers was 120:80:80 kg NPK ha^{-1} that have been applied in the form of urea, single superphosphate and muriate of potash, respectively. At the time of final land preparation, half N and full applications of P and K were applied as a basal, and the remaining half N was top dressed 30–35 days following transplanting. The necessary standard plant protection precautions were taken. To assure continuous harvest over an extended time, the crop was harvested initially in the first week of February of the next year and continued at staggered dates. Nearly eighty plants were accommodated in each experimental plot. Five plants from the center of each plot were randomly selected for recording the head weight, head diameter and head yield. To eliminate the border effect, the harvested plants and soil from the root zone were removed from each plot, leaving the plants at the edge undisturbed. Plants' edible parts were separated for analysis of As.

2.3. Irrigation scheduling

For the proper establishment of seedlings, common bucket irrigation was applied to each plot at the time of transplanting at a depth of 20 mm. The recommended surface irrigation scheduling was started in the third week of November every year due to almost constant rainfall amounts and weekly pan evaporation. Thereafter, it was continued at 13–14-day intervals before 10–12-day crop harvesting. Water was applied in a furrow at a depth of 40 mm for irrigation. Throughout the whole growing season, broccoli and cauliflower received four irrigations. Using a Parshall flume, the amount of water used in each irrigation treatment was determined to compute the total water use of the crops.

Drip irrigation was planned at 1.0 and 0.7 of pan evaporation replenishment (E_0) for an interval of 3 days. Daily evaporation data were recorded from October–February for the year 2018-19 and 2019–20 from a US Weather Bureau Class A Pan Evaporimeter installed inside the research area. Groundwater was drawn from a deep tubewell to a 500 L capacity overhead tank that was operational at a height of 3.3 m above the local ground level for the gravity-fed drip irrigation system. At a pressure of 6500 kg m^{-2} and an average discharge rate of 1.8 L/h, lateral drip lines (12 mm in diameter) were installed between two rows of emitters/drippers spaced 25 cm apart in gravity drip irrigation treatments. On either side of the plant, 30 cm away, two drippers were provided. Due to changing irrigation needs over the course of the cropping season, dripper discharge and operation times were modified based on the precise volume of water needed. In each experimental year, irrigation was started on November 20 and continued until January 31. A total of 23 irrigations were applied to various gravity-fed drip systems and the total water applied was computed.

For sprinkler treatments, 1.0 and 0.7 of pan evaporation replenishment (E_0) was adopted. Daily evaporation data were recorded from October–February for the year 2018-19 and 2019–20 from a US Weather Bureau Class A Pan Evaporimeter installed inside the research area. One micro-sprinkler with the discharge of 60 L/h was placed in each plot with a riser height of 0.60 m at an operating pressure 10,000 kg m^{-2}. The low-density polyethylene (LDPE) lateral of 14 mm diameter was used. These laterals were connected to a 25 mm galvanized iron (G.I.) sub main which was subsequently connected to 50 mm of G.I. main pipe. The micro-sprinkler with stakes having a wetting diameter of 3.0 m was connected with lateral. The average uniformity coefficient was 88%. A buffer strip of width 1.0 m was left between treatment plots. The irrigation for micro-sprinkler system was scheduled at 3 days interval thus attributing to 23 irrigations similar to the drip system. From the discharge, the number of irrigation and running time, the total amount of water applied in each crop was computed.

2.4. Water productivity

The ratio of agricultural production to irrigation water applied was calculated as irrigation water productivity (IWP) (Poddar et al., 2022).

$$IWP = Ya / IW$$

IWP = irrigation water productivity (kg m^{-3}), Ya = head yield (kg ha^{-1}) and IW = irrigation water applied (m^3 ha^{-1}).

2.5. Collection and preparation of soil and plant samples

From the experimental plots, the initial and post-harvest soil samples (0–15 cm) were gathered, air-dried, pulverized, sieved (2–mm), and then kept in pre-marked airtight polythene packets. The physicochemical characterization approach was adopted using standard analytical techniques. Soil pH and electrical conductivity were measured in a 1:2 soil:water solution (Datta et al., 1997; Jackson, 1973). The usual methods of Subbiah and Asija (1956), Olsen and Sommers (1982), and Knudsen et al. (1983) were used to measure soil N, P, and K respectively; while Walkley and Black's (1934) method was used to measure soil organic C. For measuring clay content, a hydrometer was used (Bouyoucos, 1962). Olsen ($NaHCO_3$) extractable As (Johnston and Barnard, 1979) was used to quantify the amount of bioavailable As in the soil, whereas Sparks et al. (2006) approach was used to determine the total amount of As in soil and water samples. The plant samples were collected at harvest and washed with tap water followed by double-distilled water and then diluted hydrochloric acid followed by re-washing with double-distilled water. The samples were then chopped and dried for 24 h at 60 °C in an air oven. Whatman No. 42 filter paper was used to filter the dry materials after they had been crushed and digested with a mixture of acids consisting of HNO_3, $HClO_4$, and H_2SO_4 in a ratio of 10:4:1 (v/v) (Jackson, 1973).

2.6. Instrumental condition

Atomic Absorption Spectrophotometer (AAS) was used to determine the amount of As in plant digest and soil extract. 5 ml of the aliquot was taken in 50 ml volumetric flask, 5 ml of concentrated HCl and 1 ml. of mixed reagent [5% KI (w/v) + 5% Ascorbic acid (w/v)] were added to it, kept for 45 min to ensure complete reaction and the volume was made up to 50 ml. The resultant solution was analyzed in a PerkinElmer Atomic Absorption Spectrophotometer with Flow Injection Analysis System (FIAS 400) at $\lambda_{max} = 193.7$ nm where the carrier solution was 10% v/v HCl, the reducing agent (to ensure all As species be reduced to AsH_3 and to be measured against a calibration with standard As^{+3} solution) was 0.2% $NaBH_4$, in 0.05% NaOH (Sparks et al., 2006).

2.7. Quality control and quality assurance

The analytical methodology of As determination was validated through the use of rice standard reference material (SRM1568a) established by the National Institute of Standards and Technology (NIST). The current PerkinElmer AAnalyst 200 AAS attached with Flow Injection for

Atomic Spectroscopy (FIAS) Systems at λ_{max} = 193.7 nm exhibited As concentration as 287 ± 8.1 μg kg^{-1}, thus exhibiting good agreement with the certified value of 290 ± 30 μg kg^{-1} for SRM1568a. Every batch of 30 samples included analysis of one standard reference material, two blank reagents, and accuracy validation in triplicates. The method precision was assessed with respect to relative standard deviation (RSD) and minimum detection limit (MDL) of the instrument was determined (0.2 ppb). RSD ranged from 4.1 to 4.3% for As in the current experiment (Sengupta et al., 2023).

2.8. Bioaccumulation factor (BAF) of As in head of broccoli and cauliflower

The standard approach (Das et al., 2022) for calculating the ratio of the metal concentration (mg kg^{-1}) in a head of broccoli and cauliflower to the metal concentration (mg kg^{-1}) in the soil was used to calculate bioaccumulation factors (BAF).

$$BAF = (Metal_{plant})/(Metal_{soil})$$

Higher BAF denotes low soil metal deposition, easy plant component uptake and accumulation, and subsequent transmission to the food chain.

2.9. Dietary carcinogenic risk assessment

The Swedish National Food Agency describes a risk thermometer as a well-established, innovative risk characterization procedure (Sand et al., 2015). The risk thermometer compares the health-based Tolerable Daily Intake and primarily calculates the exposure to As in food (TDI). The following equation (Chowdhury et al., 2020) is used to calculate the human dietary exposure to As:

$$SAMOE = TDI / (AF_{BMR} \text{ x } AF \text{ x } SF \text{ x } E)$$

Where, TDI for As is 3.0 μg kg^{-1} $bodyweight^{-1}day^{-1}$, AF_{BMR} = Non-linear relation in dose range (1/10; BMR - Benchmark response), AF (Assessment factors) = a factor of 10 (conservative assessment), SF (Severity factor) = 100 (For cancer, the most severe category), E = Different exposure factor (here, inorganic As concentration). Based on the Severity Adjusted Margin of Exposure (SAMOE) value, Class 1 (no risk, >10), Class 2 (no to low risk, 1–10), Class 3 (low risk, 0.1–1), Class 4 (moderate to high risk, 0.01–0.1), and Class 5 (severe risk, 0.01) are the designated classes of risk in the risk thermometer (Sengupta et al., 2021).

2.10. Biochemical assay of antioxidant enzyme

An enzyme assay was carried out to analyze the antioxidant enzyme system, including SOD, GPX, and CAT as it gives an idea about As stress situation in a plant. For this test, 0.05 mol L^{-1} of phosphate buffer solution (pH 7.0) containing 1 μmol L^{-1} of EDTA was homogenized with 0.5 g of fresh broccoli or cauliflower heads in a pestle and mortar. The supernatant from the centrifugation of the homogenized mixture at 12,000×g for 15 min was utilized for the enzyme assay. The aforementioned actions were completed at 4 °C. SOD's ability to prevent the photochemical reduction of nitroblue tetrazolium was used to measure its activity (Gao et al., 2009). CAT activity was assayed from the rate of H_2O_2 decomposition following Dhindsa et al. (1981). GPX activity was measured as the increase of absorbance due to guaiacol oxidation at 470 nm (Zheng and Huystee 1992).

2.11. Econometric approach through benefit-cost computations

Benefit-cost ratio analysis was carried out to assess the economic feasibility of the different irrigation practices. The cost of cultivation included the expenses incurred on land preparation, seed procurement, nursery raising, planting, intercultural operation and cost of mineral fertilizers, their application, plant protection measures, cost of irrigation water, harvesting and processing. The gross return was worked out using the prevailing average market price of the produce during the period as 9.53 US dollar (USD) per quintal for broccoli and 8.75 USD per quintal for cauliflower. The net return was estimated by subtracting the seasonal cost of production from the gross return. The benefit-cost ratio was calculated by dividing the net return with the cost of cultivation for the individual treatments (Saha et al., 2022).

2.12. Statistical analysis

The Shapiro-Wilk normality test was initially used to determine the normality of the two years of data on the chemical characteristics of soil and plant. Analysis of variance (ANOVA) techniques was applied to the data collected for various soils and plant attributes using SPSS 25.0 and Microsoft Excel 2016. Fisher's least significant difference (LSD) at the 5% level of probability was used to evaluate the statistical significance between the means of individual treatments (Patra and Sengupta 2022). Further, since the variation in data across the experimental years was estimated to be homogeneous by performing Bartlett's chi-square test, the year variance was pooled with the experimental error variance to draw the inferences.

3. Results and discussion

3.1. Characterization of the experimental site

The initial soils' average physico-chemical characteristics included a pH of 7.04, a low soluble salt content with an electrical conductivity (EC) of 0.38 dS m^{-1}, a medium organic carbon content (0.57%), a silty clay texture with 49.5% clay, low available nitrogen (256 kg ha^{-1}), and low available potassium (189 kg ha^{-1}), while the available phosphorus content was high (35.5 kg ha^{-1}). The topsoil (0–15 cm) has a reasonably high amount of available As (6.97 ± 2.27 mg kg^{-1}). When crops were irrigated with water from a shallow tube well (STW), it contained a significant amount of As (0.19 ± 0.11 mg L^{-1}) and resulted in significant As concentrations in broccoli and cauliflower heads of about 0.41–0.52 and 0.35–0.44 mg kg^{-1}, respectively. The high presence of As in vegetables that are cultivated in As affected areas of West Bengal, India has been widely reported (Bhattacharyya et al., 2021; Das et al., 2016; Santra et al., 2013).

Table 1
Effect of drip and sprinkler irrigation management on arsenic content in soil at harvest and edibles of broccoli and cauliflower (pooled estimate of two years).

Treatments	Broccoli		Cauliflower	
	Soil As (mg kg^{-1})	Head As (mg kg^{-1})	Soil As (mg kg^{-1})	Head As (mg kg^{-1})
Surface irrigation	8.25	0.42	7.93	0.36
Drip at 1.0 ETc	7.17	0.39	6.86	0.32
Drip at 0.7 ETc	6.66	0.38	6.52	0.30
SEm(±)	***0.27***	***0.03***	***0.12***	***0.03***
LSD (p = 0.05)	***0.82***	***0.09***	***0.37***	***0.08***
Surface irrigation	6.90	0.39	8.25	0.38
Sprinkler at 1.0 ETc	5.90	0.37	7.21	0.37
Sprinkler at 0.7 ETc	5.71	0.32	6.87	0.32
SEm(±)	***0.18***	***0.01***	***0.17***	***0.01***
LSD (p = 0.05)	***0.57***	***0.03***	***0.53***	***0.02***

3.2. As content of the soil and vegetable edible parts under imposed treatments

The effect of micro-irrigation treatments on the As content of the soil as well as the edible parts of broccoli and cauliflower have been presented in Table 1. In all cases, the employment of drip and sprinkler irrigation was able to reduce As content in soil and crop edible parts as compared to surface irrigation. The mean value of soil As for surface irrigation across the years ranged from 6.90 to 8.34 mg kg^{-1} (for broccoli) and 7.12–8.41 mg kg^{-1} (for cauliflower); while the same for drip and sprinkler irrigation ranged from 5.52 to 7.21 mg kg^{-1} (for broccoli) and 6.16–7.25 mg kg^{-1} (for cauliflower) respectively. For both drip and sprinkler systems imposition of deficit irrigation at a greater extent (0.7 E_0) was found to have lower As content as compared to deficit irrigation at 1.0 E_0 presumably due to the lower level of irrigation using contaminated water.

The effect of the imposed drip and sprinkler irrigation in different deficit schedules also had conspicuous effects on the As accumulation in the edible heads of broccoli and cauliflower. The results as evident from Table 1 suggested that the mean value of edible head As for surface irrigation across the years ranged from 0.39 to 0.42 mg kg^{-1} (for broccoli) and 0.36 to 0.38 mg kg^{-1} (for cauliflower); while the same for drip and sprinkler irrigation ranged from 0.32 to 0.39 mg kg^{-1} (for broccoli) and 0.30 to 0.37 mg kg^{-1} (for cauliflower) respectively. Similar to the pattern of soil As for both drip and sprinkler systems imposition of deficit irrigation at a greater extent (0.7 E_0) was found to have lower As content as compared to deficit irrigation at 1.0 E_0. The percentage reduction in the As content in the broccoli and cauliflower edible parts under applied micro-irrigations at 1.0 and 0.7 E_0 as compared to conventional surface irrigation has been provided in Fig. 1. Results revealed that micro-irrigation reduced the As accumulation in edible parts by 6.78–15.6% for broccoli and 5.08–16.6% for cauliflower over surface irrigation.

Such reduction in the level of heavy metals or contaminants under the influence of micro-irrigation is not uncommon. Abd–Elrahman et al. (2022) reported deficit irrigation at 60% of ET was able to reduce the accumulation of nitrate in the edible parts of lettuce (*Lactuca sativa*). Further similar trends have also been reported for Cu, Zn, Cd, Pb, Cr, and Ni for soil and plant edible loads of corn and wheat (Asgari and Cornelis, 2015); and also in the order of Fe > Zn > Cu > Cr in case of vegetables by Qureshi et al. (2016). The most fascinating feature that led to the development of this research is that there is not a single report of As uptake pattern under such micro-irrigation systems. All the studies have unequivocally established that whenever the source of irrigation water is contaminated it is safer to reduce the quantity of irrigation so that less amount of the contaminant finds its entry in the soil-plant system, which might be the reason for lower As accumulation under deficit micro-irrigation regimes in the current study as well.

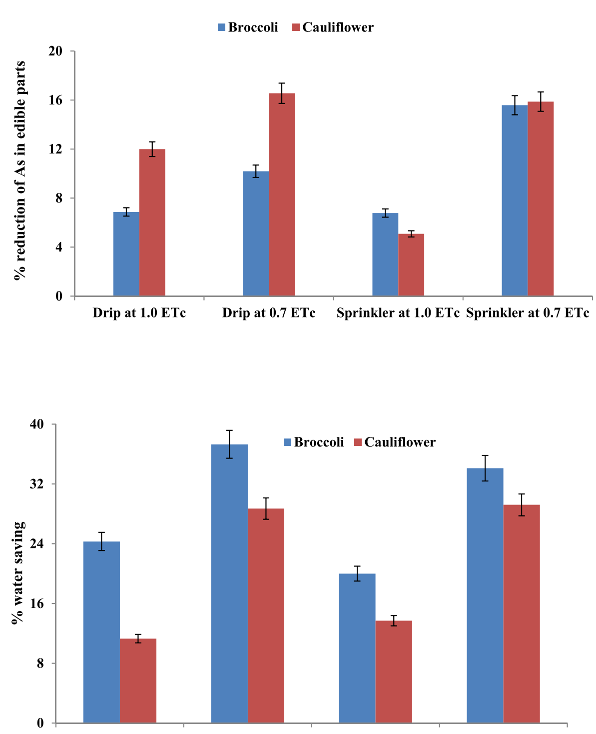

Fig. 1. Percentage change in arsenic content and water saving for drip and sprinkler treatments over surface irrigation.

3.3. BAF of As in edible parts under irrigation treatments

The Bioaccumulation Factor (BAF) was typically used to calculate the amount of heavy metal transfer from soil to the edible crop plant sections (Mani et al., 2021). The amount and type of heavy metals, the kind of plant species, the physicochemical properties of the soil, etc., all have an impact on the rate of transfer and accumulation of these heavy metals from soil to crop plants (Chang et al., 2014). In order for heavy metals to enter and move through the food chain, they must first go from the soil to edible plant parts (Naser et al., 2012; Sharma et al., 2018). The bioaccumulation factor of As analyzed in the edible heads of vegetable crops under the applied micro-irrigation treatments presented in Fig. 2 revealed a range exceeding 0.04–0.06. Following a similar pattern of As in soil and crop edible parts, surface irrigation had the maximum BAF, while for both drip and sprinkler systems imposition of higher deficit irrigation (0.7 E_0) had the lowest BAF followed by deficit irrigation at 1.0 E_0. The efficiency of drip irrigation was more pronounced in reducing As compared to sprinkler irrigation.

Previous studies have shown that crops like broccoli have a propensity to heavily absorb arsenic from soil and irrigation water and accumulate in their edible components like stems/leaves or fruits (Sipter et al., 2008); this poses serious health risks to the community who consumes these vegetables (Poddar et al., 2022). Lead (57.6 mg kg^{-1}) and cadmium (17.8 mg kg^{-1}) levels in radish have been found to be alarmingly high in Titagarh, India (Gupta et al., 2008). Even though edible parts of broccoli have been found to contain high levels of lead (0.38 mg kg^{-1}) and cadmium (0.79 mg kg^{-1}) in China (Luo et al., 2011), there have only been a few reports of arsenic contamination in broccoli and cauliflower up to this point, and BAF indices have not yet been developed for assessing the risk potential conclusively. Although the BAF of As in the head was not high, it might be a clue that, despite not being extensively stored in the edible component, excessive buildup of As in leaves might have negatively impacted the plant's ability to

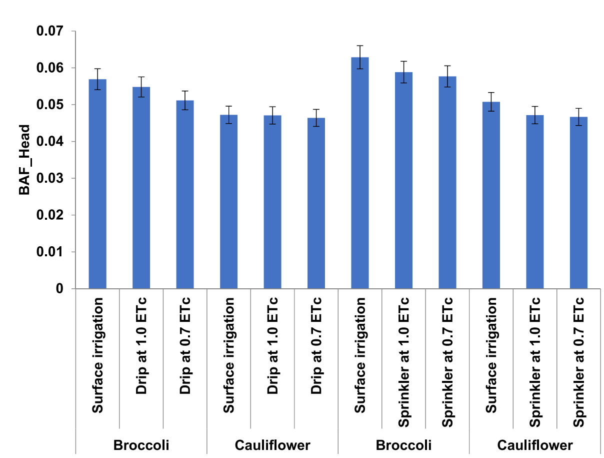

Fig. 2. Bioaccumulation factor (BAF) of arsenic in the edibles of broccoli and cauliflower under drip and sprinkler treatments over surface irrigation.

photosynthesize, which in turn would have reduced the yield. Numerous experts have long claimed that As disrupts the photosynthetic cycle and affects plant metabolic processes (Gunes et al., 2010; Khalid et al., 2017; Rafiq et al., 2017).

3.4. Head yield and characteristics under applied irrigation treatments

The effect of micro-irrigation treatments *vis-à-vis* surface irrigation on the edible head yield and yield attributing characters in broccoli and cauliflower have been presented in Table 2. The yield attributing characters like head diameter and head weight have been equally important for marketable quality delineation of the produce. The results revealed that all the parameters of head yield, head diameter and head weight improved under drip and sprinkler irrigations at 1.0 E_0 as compared to surface irrigation with the former being more efficient. The mean values of head yield, head diameter and head weight under surface irrigation ranged from 15.4 to 16.1 t ha^{-1}, 14.6–14.9 cm, and 311–320 g (for broccoli) and 19.9–21.3 t ha^{-1}, 12.0–12.2 cm, and 404–531 g (for cauliflower); while for micro-irrigations under optimum scheduling the values ranged from 15.9 to 16.9 t ha^{-1}, 14.6–15.1 cm, and 331–341 g (for broccoli) and 21.3–22.7 t ha^{-1}, 12.1–12.3 cm, and 417–539 g (for cauliflower). On the contrary, more deficit irrigation at 0.7 E_0 had a considerable reduction in the head yield, head diameter and head weight as evident from Table 2. This can possibly be attributed to the fact the lower quantity of water application under micro-irrigation at 0.7 E_0 could not possibly meet up with the water required for optimum growth and productivity of the crops leading to poorer estimates.

Drip and sprinkler irrigations at 1.0 E_0 were linked to the greatest increase in head yield and the factors affecting growth and production. Increased watering rates could have helped maintain the root zone's optimal soil water availability throughout the crop's growth phases, lowering soil water stress and plant cell turgid pressure, and ultimately boosting vegetative growth, yield metrics, and head yield (Kumar and Sahu, 2013; Ramadan and Omar, 2017). Increased micro-irrigation regimes might have improved leaf area, which could lead to more photosynthetic area, faster carbohydrate production, and efficient transport of photosynthates to the head, which would increase head size and yield (Agrawal et al., 2018). Conversely, higher degrees of deficit irrigation had minor effects on growth and yield parameters and lowered yield, most likely as a result of increased soil water stress that did not meet the physiological water requirements of the plants (Saha et al., 2022).

3.5. Water productivity and water saving under micro-irrigation regimes

In the current study adoption of micro-irrigation regimes was responsible for reducing the total water use by the crop and improving the water productivity in terms of more crops per drop of water. The results as evident from Table 2 suggested that there was substantial water use by the crop when surface irrigation was provided (406–412 mm for broccoli and 408–415 mm for cauliflower) especially when the pooled estimate of both the study years was considered. On the contrary under the imposition of micro-irrigation regimes the total water use by the crop declined to a considerable extent (258–325 mm for broccoli and 291–362 mm for cauliflower). The percentage reduction in the water use in the broccoli and cauliflower under applied micro-irrigations at 1.0 and 0.7 E_0 as compared to conventional surface irrigation has been provided in Fig. 1. Results revealed that micro-irrigation resulted in water saving by 6.78–15.6% for broccoli and 20.0–37.3% for cauliflower over surface irrigation. The water productivity was found to improve in micro-irrigation systems as compared to surface irrigation (Table 2) as evidenced by the values of 3.80–3.90 kg m^{-3} (surface irrigated broccoli) and 4.80–5.09 kg m^{-3} (surface irrigated cauliflower) on one hand; and 4.90–5.72 kg m^{-3} (micro-irrigated broccoli) and 5.93–6.44 kg m^{-3} (micro-irrigated cauliflower) on the other.

Since a larger volume of water was applied each time, the lowest water productivity with surface irrigation might be attributed to the loss of water in deep percolation as a result of uneconomic water use for crop production. On the other hand, under varying deficit micro-irrigation levels, a substantially higher CWP was obtained by applying water directly into the rooting zone at the appropriate time and avoiding water losses through evaporation, runoff, and deep percolation (Comas et al., 2019; Rajurkar et al., 2012). The deficit irrigation scenario produced the highest CWP due to the full water usage for proportionate yield gain (Patra and Sengupta, 2022; Saha et al., 2022).

3.6. Effect of micro-irrigation on antioxidant enzyme profile assay

By causing the generation of ROS like the superoxide radical ($O_2^{-\bullet}$), hydrogen peroxide (H_2O_2), hydroxyl radical (•OH), and singlet oxygen (•O_2), heavy metals cause oxidative stress in higher plants (Devi and Prasad 1998). According to Xiao et al. (2006), oxidative stress happens when ROS overabundance results in an imbalance in redox homeostasis, which can cause irreversible metabolic malfunction and cell death. SOD, GPX, and CAT are examples of oxygen-scavenging enzymes that are part of a crucial defence mechanism that reduces oxidative damage (Li and

Table 2
Effect of drip and sprinkler irrigation management on growth, yield and water productivity of broccoli and cauliflower (pooled estimate of two years).

Treatment	Broccoli					Cauliflower				
	Head diameter (cm)	Head weight (g)	Head yield (t ha^{-1})	Total water use (mm)	Water productivity (kg m^{-3})	Head diameter (cm)	Head weight (g)	Head yield (t ha^{-1})	Total water use (mm)	Water productivity (kg m^{-3})
Surface irrigation	14.9	320	16.1	412	3.90	12.2	531	21.3	408	5.09
Drip at 1.0 ETc	15.1	341	16.9	312	5.42	12.3	539	22.7	362	6.12
Drip at 0.7 ETc	14.3	304	14.8	258	5.72	11.5	481	19.3	291	6.44
SEm(±)	***0.22***	***9.96***	***0.49***	-	-	***0.16***	***9.50***	***0.51***	-	-
LSD (p = 0.05)	***0.69***	***30.6***	***1.54***	-	-	***0.48***	***29.2***	***1.56***	-	-
Surface irrigation	14.5	311	15.4	406	3.80	12.0	404	19.9	415	4.80
Sprinkler at 1.0 ETc	14.6	331	15.9	325	4.90	12.1	417	21.3	358	5.93
Sprinkler at 0.7 ETc	13.8	296	14.6	267	5.48	11.5	372	18.1	294	6.13
SEm(±)	***0.21***	***9.67***	***0.34***	-	-	***0.18***	***8.18***	***0.48***	-	-
LSD (p = 0.05)	***0.66***	***29.8***	***1.04***	-	-	***0.55***	***25.1***	***1.46***	-	-

Wang 2002; Tie et al., 2007). Different plant cultivars accumulate heavy metals differently, which may be explained in part by tolerance of the antioxidant system.

In the current experiment, the treatments of micro-irrigation were able to conspicuously alter the profile of the antioxidant enzymes *vis-à-vis* surface irrigation (Fig. 3). In all cases, the adoption of drip and sprinkler irrigation in both the study years and both the crops declined the quantity of the enzymes. This can simply be attributed to the fact that if less amount of contaminated water was applied as irrigation then the accumulation of As will be lowered in the soil-plant system, reducing the chance of As stress in the crops and manifestation of higher SOD, GPX, and CAT enzyme status. Conversely, surface irrigation accumulated more As in soil and crop edible parts leading to greater stress. Among the three enzymes, the fluctuations in GPX and CAT were comparatively less because of their possibly higher substrate specificity. The finding was further verified through a correlation study of head As with the enzyme profile suggesting greater association with SOD ($r = 0.76^*$) followed by that of CAT ($r = 0.65^*$) and GPX ($r = 0.35$).

Increased reactive oxygen species (ROS) production in response to arsenic exposure showed increased oxidative stress in terms of lipid peroxidation. It is well known that plant heavy metal toxicity causes intricate biochemical reactions and a variety of protective mechanisms aimed at detoxifying ROS like SOD, GPX, and CAT, which were frequently produced in plants as a result of metal contamination (Srivastava and Sharma, 2013). The primary superoxide ($O_2^{-\bullet}$) scavenger SOD also acts as the first line of defence against cellular damage brought on by environmental stress (Hasan et al., 2009). SOD transforms the highly reactive O_2 into H_2O_2 (Gao et al., 2009). The activity of SOD is closely related to that of CAT, a heme-containing tetrameric protein that converts the H_2O_2 generated by SOD into H_2O and O_2 (Halliwell and Gutteridge 1989; Miyake and Asada 1994). Another crucial class of antioxidant enzymes, peroxidases (GPX), is crucial for preserving the stability and integrity of cell membranes (Zhang et al., 2007). Increased activity of GPX under conditions of heavy metal stress can cause the removal of damaging peroxide molecules in plant cells (Yan et al., 1997). Due to its limited substrate affinity, CAT performs H_2O_2 scavenging less effectively than GPX. Therefore, the primary reaction to heavy metals is a rise in SOD activity as long as the stress of heavy metals does not exceed the defence capability of the plant (Du et al., 2017; Siedlecka and Krupa 2002).

3.7. Economic analysis of broccoli and cauliflower cultivation under applied interventions

The benefit-cost analysis for appraisal of the economic feasibility of different micro-irrigation treatments along with the surface irrigation

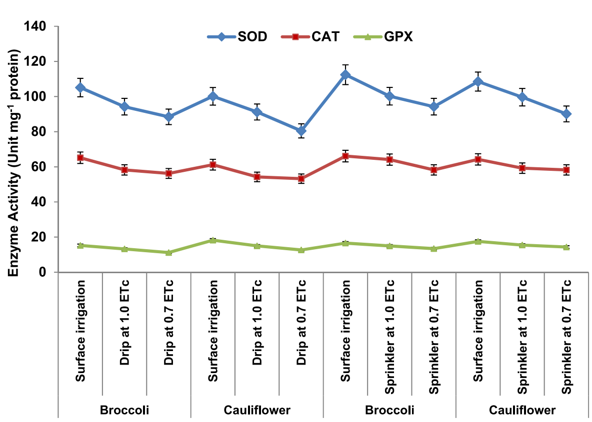

Fig. 3. Effect of drip and sprinkler irrigation treatments on SOD, CAT and GPX enzyme of broccoli and cauliflower edibles expressed as mean of seven replications ±SD.

Table 3
Economics of production of cauliflower and broccoli under applied interventions (pooled estimate of two years).

Broccoli				
	Cost of Cultivation (USD/ha)	Gross Return (USD/ha)	Net Return (USD/ha)	BC Ratio
Surface irrigation	793	1532	739	0.93
Drip at 1.0 ETc	754	1612	858	1.14
Drip at 0.7 ETc	720	1411	691	0.96
Surface irrigation	793	1473	680	0.86
Sprinkler at 1.0 ETc	763	1517	754	0.99
Sprinkler at 0.7 ETc	752	1398	645	0.86
SEm(±)	***15.56***	***28.52***	***15.24***	***0.04***
LSD (p = 0.05)	***45.56***	***100.52***	***41.25***	***0.09***
Cauliflower				
	Cost of Cultivation (USD/ha)	**Gross Return (USD/ha)**	**Net Return (USD/ha)**	**BC Ratio**
Surface irrigation	862	1868	1006	1.17
Drip at 1.0 ETc	819	1990	1171	1.43
Drip at 0.7 ETc	783	1686	903	1.15
Surface irrigation	862	1747	885	1.03
Sprinkler at 1.0 ETc	829	1861	1032	1.25
Sprinkler at 0.7 ETc	818	1576	759	0.93
SEm(±)	***17.36***	***33.51***	***15.35***	***0.08***
LSD (p = 0.05)	***51.25***	***110.45***	***48.25***	***0.15***

USD refers to US dollar; BC Ratio refers to Benefit-Cost Ratio.

for broccoli and cauliflower has been given in Table 3. Results showed that the seasonal cost of production increased with increase in quantity or amount of irrigation more evidently from surface irrigation than micro-irrigation. Maximum gross return (1612 USD ha^{-1}) and net return (858 USD ha^{-1}) were obtained from drip irrigation at 1.0 ETc for broccoli while for cauliflower adoption of drip irrigation at 1.0 ETc resulted in a maximum gross return (1990 USD ha^{-1}) and net return (1171 USD ha^{-1}). The benefit cost ratio had the maximum value for drip irrigation at 1.0 ETc for broccoli (1.14) and cauliflower (1.43). Adoption of sprinkler irrigation at 1.0 ETc also resulted in a significantly high benefit cost ratio, lower than drip irrigation. Deficit irrigation at 0.7 ETc reduced the benefit cost ratio while surface irrigation had the lowest advantage in terms of cost and benefit. A significant drop in gross return owing to lower crop yield as well as more water application resulted in other treatments to be poor from the economic angle (Saha et al., 2022).

3.8. Relating the head As with soil and irrigation water As

From the product of the total quantity of the water used by the crops during the entire growth stage and the mean As content of the groundwater, the total quantity of As that is accumulated through the application of surface and micro-irrigation treatments was computed. In order to determine how well irrigation water and soil contribute to the head As content of broccoli and cauliflower, linear regression modelling was then used among the head As, soil As, and irrigation water As. Because irrigation water was typically supplied to the soil before being absorbed by the crop, deciphering the likely pathway reveals that the uptake of As in crops was more closely related to soil As than to irrigation water As. Similar explanations were also provided by Mandal

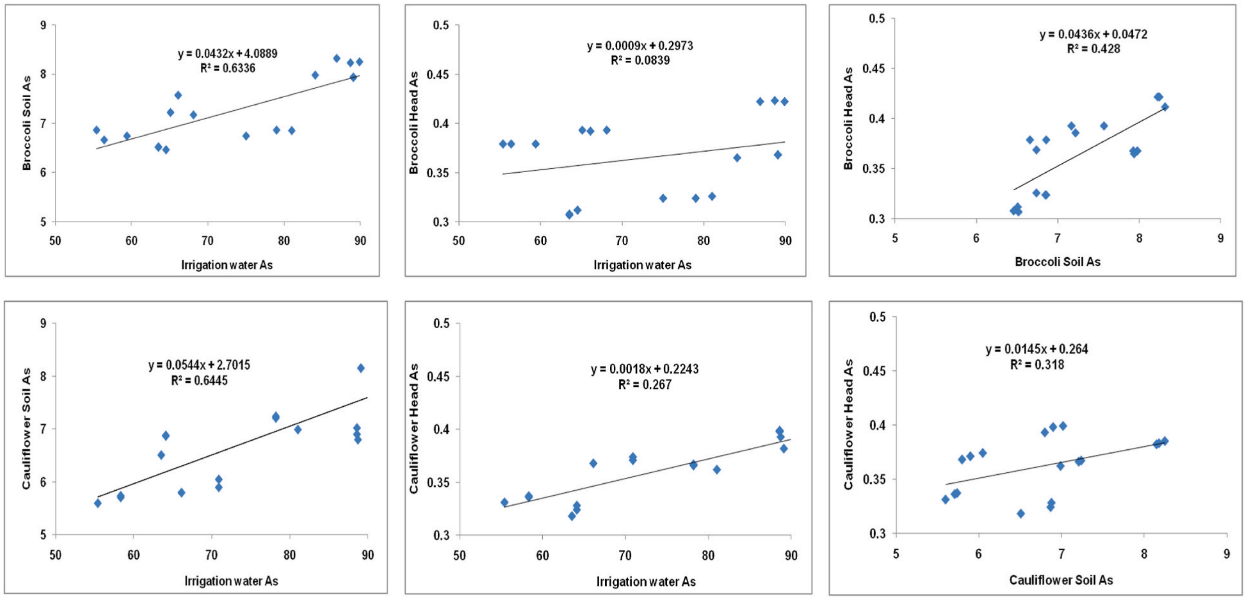

Fig. 4. Relationship of soil As, irrigation water As and head As of broccoli and cauliflower (mean of 42 observations).

et al. (2021) in a meta-analysis involving rice that accumulation of As in crop edible parts is directly related to soil As rather than As from irrigation water.

The results of the current study (Fig. 4) revealed a significant positive relationship between irrigation water As and soil As ($R^2 = 0.63$ and 0.65 for broccoli and cauliflower respectively) which suggested that more the level of contamination in the source of irrigation water it would sink in soil, which act as a reservoir, and thus the application of a lower quantity of water through micro-irrigation regimes can be a clue to solve the problem of As toxicity in vegetable crops having export potential (Bhattacharyya et al., 2021). The positive but non significant value of relationship among soil As and head As ($R^2 = 0.43$ and 0.32 for broccoli and cauliflower respectively) as well as irrigation water As and head As ($R^2 = 0.08$ and 0.27 for broccoli and cauliflower respectively) suggested that the soil has some specific features by virtue of which they could resist the uptake of As into the crop edible parts.

Several soil physicochemical properties like pH, organic carbon content, available phosphorus, iron, zinc, and even microbial properties have been delineated to decipher the reasons, of which the first two have been given the most impetus by a maximum of the studies (Bhattacharyya et al., 2021; Mandal et al., 2019; Sengupta et al., 2021). Since CO_2 lowers the pH of even acid soils (Kumari et al., 2021), it is likely that the large-scale pH decline after irrigation is caused by the accumulation of CO, which is a byproduct of aerobic bacterial respiration. This further inhibits the As translocation. Most soils have an adequate amount of organic carbon, which also serves as a sink for As. The application of organic manure immobilizes, adsorbs, binds, or co-precipitates As in situ, which can affect the presence, availability, and mobility in soils and aquatic habitats, according to a number of studies. By producing negatively charged adducts, the complexation of arsenite with humic acid *via* phenolic, carboxylic, amino, and sulfhydryl functional groups may act as the binding sites for As (Sengupta et al., 2021, 2022b).

3.9. Dietary risk of As through vegetable consumption

It is true that a detailed examination of As buildup in agricultural produce and its related dietary concerns has become necessary due to the increased threat of As entering other non-contaminated regions through foods cultivated in highly As-contaminated locations. Rice is consumed as a staple food with vegetables about three times per day in rural West Bengal, India, and Bangladesh (Bhattacharyya et al., 2021; Signes-Pastor et al., 2008). The consumption of other grains, fruits, and animal proteins (e.g., eggs, fish, chicken, mutton, etc.) is typically negligible (Halder et al., 2013).

The 'Risk thermometer' and the calculated 'SAMOE' value for As toxicity through cultivated broccoli and cauliflower under the surface and micro-irrigation regimes showed varying concern levels of risk from class 4 (moderate-high) to about class 3 (low risk) depending on As concentration (Fig. 5). The surface irrigation showed the highest SAMOE (0.07) while sprinkler irrigation and drip irrigation had much lower risks (SAMOE values of 0.09 and 0.10, respectively). Thus consumption of such contaminated vegetables edible parts alone or in conjunction with other dietary elements can increase the carcinogenic risk of As in human body (Chowdhury et al., 2020; Sengupta et al., 2021).

4. Conclusion

The extensive use of As-contaminated water for agriculture irrigation causes significant dietary contamination of the human food chain and poses serious health risks. Rural residents' main staple foods are rice and vegetables, thus materials that reduce the amount of As in them are very important. In spite of a number of mitigation strategies that have been adopted, a severe paucity exists regarding the use of micro-irrigation as a viable tool for reducing the As load in cultivated crops. The present study has made a modest attempt to devise a strategy of using drip and sprinkler irrigation regimes in a much more efficient, sustainable and eco-friendly approach to curb As pollution on one hand and improve water productivity on the other. Deficit irrigation schemes in terms of drip and sprinkler at 1.0 and 0.7 E_0 resulted in a reduction in As in crop edible parts to an extent of 16.6%; improved the head weight, diameter and yield of broccoli and cauliflower and resulted in saving of precarious water resources to an extent of 37.3%. The As stress reduction under drip and sprinkler reduced the activity of antioxidant enzymes and also made carcinogenic dietary risk parameters somewhat benign. The results as obtained for broccoli and cauliflower as two major cultivated cruciferous vegetable crops have been quite promising as they fetch high value in the market and require moderate level of irrigation, and this promise can be adopted in other high value vegetables. Thus, based on the competitive advantage, we may propose that drip irrigation without water stress can be a boon to vegetable farming in the As contaminated belts not only for saving water resources but also for improving crop productivity and As toxicity. However, the most commonly cultivated

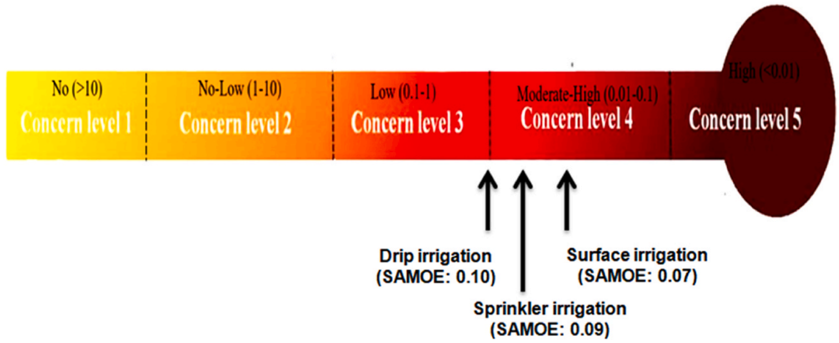

Fig. 5. SAMOE based risk thermometer scale showing the class of arsenic toxicity through broccoli and cauliflower consumption under drip and sprinkler system as compared to surface irrigation.

crop rice requires standing water of about 3–4 cm, therefore the applicability of the concept of micro-irrigation to solve the problem of As pollution is severely hindered. Further to make a robust recommendation focus must be given to up-scaling this study in diverse physiographic locations globally through a paired sampling of soil, water and crops.

Research involving human participants and/or animals

This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent

Informed consent was obtained from all individual participants included in the study.

Author contributions

Sudip Sengupta: Methodology, Investigation, Data curation, Software and Writing- Original draft preparation; Sanmay Kumar Patra: Conceptualization, Methodology, Supervision; Aritri Laha: Investigation, Data curation; Ratneswar Poddar: Investigation, Data curation; Kallol Bhattacharyya: Conceptualization, Methodology, Supervision; Jajati Mandal: Data curation, Writing- Reviewing and Editing; Pradip Dey: Methodology, Supervision; Writing- Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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