RESEARCH PAPER

Industrial Effluent Irrigation Modulates Bioactive Constituents and Safety Profile of *Momordica charantia* L. Implications for Nutraceutical Quality

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ABSTRACT

The reuse of industrial effluents for irrigation is increasingly being considered as a sustainable solution to water scarcity in agriculture. The present study was undertaken to evaluate the effect of paper board industry effluent on biochemical constituents, nutrient content, and heavy metal accumulation in bitter gourd (*Momordica charantia* L.). The experiment was conducted using five treatments: T_1 (rainwater irrigation as control), T_2 (25% effluent), T_3 (50% effluent), T_4 (75% effluent), and T_5 (100% effluent), under a controlled soilless cultivation system. The results indicated that effluent irrigation did not significantly influence key biochemical parameters, including ascorbic acid, charantin, and total chlorophyll content. The values of these constituents remained within a narrow range across all treatments, suggesting that crop quality and nutritional attributes were not adversely affected. Similarly, macronutrient (nitrogen, phosphorus, potassium) and micronutrient content and uptake showed no significant variation among treatments, indicating that effluent application maintained nutrient balance in plant tissues. Importantly, heavy metals such as cadmium (Cd), nickel (Ni), chromium (Cr), and lead (Pb) were below detectable limits in all plant parts, confirming the safety of the produce. The absence of heavy metal accumulation highlights the suitability of treated paper board industry effluent for agricultural reuse. Overall, the findings demonstrate that paper board industry effluent can be safely utilized for irrigation of bitter gourd under controlled conditions without compromising crop quality, nutrient status, or food safety. However, long-term monitoring is recommended to ensure environmental sustainability.

Keywords: Bitter gourd, Effluent irrigation, Nutrient content, Heavy metals, Charantin, Chlorophyll

How to cite this article: Subramani M, Beulah Snowin DR, Balashanmugavel B, Subramaniyan M, Raman G, Samikannu T, Sekar M, Marappan K. Industrial Effluent Irrigation Modulates Bioactive Constituents and Safety Profile of Momordica charantia L. Implications for Nutraceutical Quality. Int J Drug Deliv Technol. 2026;16(23s): 522-527.
DOI: 10.25258/ijddt.16.23s.57

INTRODUCTION

Water scarcity has emerged as one of the most critical challenges affecting agricultural productivity worldwide, particularly in arid and semi-arid regions. Increasing competition for freshwater resources due to rapid population growth, industrialization, and climate variability has necessitated the exploration of alternative water sources for irrigation. In this context, the reuse of treated industrial effluents has gained considerable attention as a viable and sustainable option for agricultural water management (Qadir *et al*., 2010). The utilization of such effluents not only helps conserve freshwater resources but also promotes the recycling of nutrients contained in wastewater. Among various industrial sectors, paper board industries are known to generate substantial quantities of wastewater during different stages of processing. This effluent often contains organic matter, dissolved solids, and essential plant nutrients such as nitrogen, phosphorus, and potassium, which can potentially support crop growth when applied in a controlled manner (Singh and Agrawal, 2008). The presence of biodegradable organic compounds may improve soil structure and microbial activity, thereby enhancing soil fertility. Consequently, the reuse of paper board industry effluent in agriculture has been considered an economically and environmentally beneficial practice.

However, despite these potential advantages, the application of industrial effluents raises several environmental and health concerns. One of the primary issues is the accumulation of toxic substances, particularly heavy metals such as cadmium (Cd), chromium (Cr), nickel (Ni), and lead (Pb), in soil and plant systems. These elements can persist in the environment for extended periods and may be taken up by crops, eventually entering the food chain and posing risks to human and animal health (Muchuweti *et al*., 2006). Long-term use of untreated or inadequately treated effluents may also lead to soil degradation, salinity buildup, and adverse effects on soil microbial communities. Effluent irrigation has been reported to influence soil physicochemical properties, plant nutrient availability, and crop productivity. Several studies have indicated that the judicious use of treated wastewater can enhance crop yield due to the additional supply of nutrients, while others have highlighted the risks associated with excessive or prolonged application (Rattan *et al*., 2005). Therefore, it is essential to evaluate the impact of effluent irrigation on both crop performance and quality parameters, particularly in edible crops where food safety is a major concern.

Bitter gourd (*Momordica charantia* L.) is an important vegetable crop widely cultivated in tropical and subtropical regions. It is highly valued for its nutritional and medicinal properties, being rich in vitamins, minerals, and bioactive compounds. Among these, ascorbic acid (vitamin C) plays a vital role as an antioxidant, while charantin is known for its hypoglycemic properties and is extensively used in traditional medicine (Grover and Yadav, 2004). The quality and safety of bitter gourd are therefore of paramount importance, especially when alternative irrigation sources such as industrial effluents are used. In addition to biochemical quality, the nutrient composition of crops is a key factor determining their productivity and nutritional value. The uptake and accumulation of macro- and micronutrients in plants can be significantly influenced by the quality of irrigation water. While effluents may supply essential nutrients, they may also alter nutrient balance and availability depending on their composition. Hence, assessing nutrient dynamics in crops irrigated with industrial effluents is crucial for understanding their agronomic suitability. Another critical aspect is the potential accumulation of heavy metals in edible plant parts. Even when present in trace amounts, these metals can accumulate over time and pose serious health hazards. Therefore, monitoring heavy metal concentrations in crops irrigated with industrial effluents is essential to ensure food safety and compliance with permissible limits. Considering the increasing need for sustainable water management practices and the potential benefits and risks associated with effluent irrigation, it is important to evaluate its impact under controlled conditions. In this context, the present study was undertaken to assess the effect of paper board industry effluent on biochemical constituents, nutrient content, and heavy metal accumulation in bitter gourd (*Momordica charantia* L.). The findings of this study aim to provide insights into the safe and efficient use of industrial effluents in agriculture, thereby contributing to resource conservation and sustainable crop production.

MATERIALS AND METHODS

The experiment was conducted in a levelled wasteland area located on the western side of the Department of Soil Science and Agricultural Chemistry, Anbil Dharmalingam Agricultural College and Research Institute (ADAC&RI), Tiruchirappalli, Tamil Nadu, India. The site is situated at 10°45′ N latitude and 78°36′ E longitude, at an altitude of 85 m above mean sea level. The region falls under the Cauvery delta agro-climatic zone, characterized by a tropical climate with an average annual rainfall of 860 mm. The experiment was conducted using a Completely Randomized Design (CRD) with five treatments and five replications, comprising T_1 (rainwater as control), T_2 (25% effluent + 75% rainwater), T_3 (50% effluent + 50% rainwater), T_4 (75% effluent + 25% rainwater), and T_5 (100% effluent). The test crop, bitter gourd (cv. CO 1), was grown for 115 days during the Rabi season in containers filled with soilless media consisting of coir pith and vermicompost. A matric suction irrigation system was used to ensure continuous water supply from bottom to top without drainage losses, with water supplied through interconnected tanks maintaining a constant level, and effluent treatments applied weekly as per the schedule. Fertigation was carried out using recommended doses of 200:100:100 kg $N:P_2O_5:K_2O$ ha^{-1}, with a 50% reduction in phosphorus and potassium due to the absence of fixation in soilless media, and water-soluble fertilizers such as urea, MAP, and MOP were applied at regular intervals along with micronutrients (Mg, Ca, Fe, Zn, Cu, and Mn) supplied through a prepared nutrient solution. Biochemical analyses included estimation of ascorbic acid using the 2,6-dichlorophenol indophenol (DCPIP) titration method, charantin using High-Performance Liquid Chromatography (HPLC), and chlorophyll following standard procedures. Plant samples were oven-dried, powdered, and analyzed for macro- and micronutrients using standard methods, while heavy metals (Cd, Ni, Cr, and Pb) were determined using standard analytical protocols. The data were statistically analyzed using analysis of variance (ANOVA), and treatment means were compared at the 5% level of significance.

RESULTS AND DISCUSSION

Biochemical Constituents

The biochemical quality parameters of bitter gourd, including ascorbic acid, charantin, and total chlorophyll content, were not significantly influenced by different concentrations of paper board industry effluent irrigation (Table 1). The ascorbic acid content ranged from 56.10 to 56.35 mg 100 g^{-1}, while charantin content varied between 0.08 and 0.10 mg g^{-1}. Similarly, total chlorophyll content ranged from 1.40 to 1.45 mg g^{-1} across treatments, indicating minimal variation. The non-significant differences in biochemical constituents suggest that effluent irrigation did not interfere with metabolic processes such as photosynthesis, antioxidant synthesis, or secondary metabolite production. Ascorbic acid is a key antioxidant involved in stress tolerance, while chlorophyll reflects photosynthetic efficiency (Murali *et al*., 2022a). The stability of these parameters indicates that the effluent did not impose physiological stress on the crop. These findings are consistent with earlier reports by Singh and Agrawal (2008), who observed minimal changes in biochemical parameters under wastewater irrigation. More recent studies also support that properly treated wastewater does not significantly alter plant biochemical composition when applied under controlled conditions (Khoshravesh and Pourgholam-Amiji, 2024). Furthermore, the absence of stress-induced biochemical alterations suggests that the effluent quality was within permissible limits and did not disrupt enzymatic or biosynthetic pathways.

Macronutrient Content

Macronutrient content, including nitrogen (N), phosphorus (P), and potassium (K), showed no significant variation among treatments (Table 2). Nitrogen content ranged from 1.498 to 1.521%, phosphorus from 0.139 to 0.144%, and potassium from 1.718 to 1.721%. The stability of macronutrient concentrations indicates that effluent irrigation maintained nutrient equilibrium within plant tissues. Nitrogen is essential for protein synthesis and vegetative growth, phosphorus plays a key role in energy transfer, and potassium regulates enzyme activation and osmotic balance. The uniform nutrient levels observed suggest that the effluent neither caused nutrient deficiency nor excess accumulation (Murali *et al*., 2022b). These results are in agreement with Rattan *et al*. (2005), who reported stable nutrient content under long-term wastewater irrigation. Recent studies also confirm that treated wastewater can act as a supplementary nutrient source without significantly altering plant nutrient composition (Al-Wabel *et al*., 2024). This indicates that the effluent used in the present study likely contained balanced nutrient levels that supported plant growth without causing nutrient imbalance.

Macronutrient Uptake

Macronutrient uptake by bitter gourd plants did not differ significantly among treatments (Fig. 1). Nitrogen uptake ranged from 1.600 to 1.627 g $plant^{-1}$, while potassium uptake ranged from 1.827 to 1.852 g $plant^{-1}$. The consistency in nutrient uptake suggests that effluent irrigation did not influence nutrient absorption efficiency. Nutrient uptake depends on root activity, nutrient availability, and moisture conditions. The matric suction irrigation system used in this study ensured continuous moisture supply, which may have facilitated uniform nutrient movement and uptake. These findings align with Qadir *et al*. (2010), who reported that treated wastewater irrigation does not significantly alter nutrient uptake patterns. Similarly, recent research indicates that nutrient uptake remains stable under controlled wastewater irrigation systems, provided that effluent quality is within safe limits (Fan *et al*., 2026). This further supports the suitability of paper board industry effluent as an alternative irrigation resource.

Micronutrient Content and Uptake

Micronutrient content and uptake, including elements such as iron (Fe), zinc (Zn), manganese (Mn), and copper (Cu), showed non-significant differences across treatments (Fig. 2). The concentrations remained within optimal ranges, indicating that effluent irrigation did not induce micronutrient toxicity or deficiency. Micronutrients are essential for enzymatic functions and metabolic processes, and their imbalance can adversely affect plant growth and quality. The observed stability suggests that the effluent did not introduce excessive trace elements or interfere with their uptake mechanisms. These findings are consistent with Muchuweti *et al*. (2006), who reported stable micronutrient levels in crops irrigated with wastewater. Recent studies also indicate that treated wastewater irrigation does not significantly affect micronutrient dynamics in crops when applied under controlled conditions (Nowwar *et al*., 2023). The results highlight that the effluent used in this study was safe with respect to micronutrient content.

Heavy Metal Accumulation

Heavy metals such as cadmium (Cd), nickel (Ni), chromium (Cr), and lead (Pb) were found to be below detectable limits in all plant parts (Table 3). This is a critical finding, as heavy metal accumulation is one of the primary concerns associated with the use of industrial effluents in agriculture. The absence of detectable heavy metals indicates that the effluent did not contribute to contamination of the edible parts of the crop. This may be attributed to the low concentration of heavy metals in the effluent or limited uptake and translocation by the plant. Additionally, the use of a soilless system may have minimized metal retention and accumulation. These results are in agreement with Singh and Agrawal (2008), who reported no significant heavy metal accumulation under treated effluent irrigation. However, contrasting findings have been reported in some recent studies, where untreated or poorly treated wastewater led to increased heavy metal accumulation in crops (Penzy *et al*., 2023; Singh *et al*., 2024). Similarly, health risk assessments have highlighted the potential dangers of long-term wastewater irrigation due to metal buildup in soil–plant systems (Journal of Food Composition and Analysis, 2024). The overall results demonstrate that paper board industry effluent, when used under controlled conditions, does not adversely affect biochemical quality, nutrient composition, or heavy metal accumulation in bitter gourd. The absence of significant differences across treatments indicates that the effluent was compatible with plant growth and metabolic functions.

CONCLUSION

The present study demonstrates that paper board industry effluent can be safely used for irrigation of bitter gourd (*Momordica charantia* L.) up to 100% concentration under controlled conditions. The effluent irrigation did not significantly influence biochemical constituents such as ascorbic acid, charantin, and chlorophyll content, indicating the preservation of crop quality and nutritional value. Macronutrient and micronutrient content and their uptake remained stable across treatments, suggesting that the effluent did not disrupt nutrient balance or plant metabolism. Importantly, heavy metals such as Cd, Ni, Cr, and Pb were below detectable limits in all plant parts, confirming the safety of the produce. The findings highlight the potential of treated industrial effluent as an alternative irrigation resource, contributing to water conservation and nutrient recycling. However, recent studies emphasize that long-term use of wastewater may lead to gradual accumulation of contaminants and potential health risks (Fan *et al*., 2026; Singh *et al*., 2024). Therefore, continuous monitoring and long-term evaluation are essential to ensure environmental sustainability and food safety (Qadir *et al*., 2010).

Table 1. Effect of paper board industry effluent on biochemical constituents of bitter gourd

Treatment	Ascorbic acid (mg 100 g^{-1})	Charantin (mg g^{-1})	Total chlorophyll (mg g^{-1})
T_1 - Control (Rainwater)	56.10	0.08	1.40
T_2 - 25% Effluent	56.18	0.09	1.42
T_3 - 50% Effluent	56.22	0.09	1.43
T_4 - 75% Effluent	56.30	0.10	1.44
T_5 - 100% Effluent	56.35	0.10	1.45
SEd	0.12	0.01	0.02
CD (p = 0.05)	NS	NS	NS

Table 2. Effect of paper board industry effluent on macronutrient content (%) in bitter gourd

Treatment	Nitrogen (%)	Phosphorus (%)	Potassium (%)
T_1 - Control	1.498	0.139	1.718
T_2 - 25% Effluent	1.505	0.140	1.719
T_3 - 50% Effluent	1.512	0.142	1.720
T_4 - 75% Effluent	1.518	0.143	1.721
T_5 - 100% Effluent	1.521	0.144	1.721
SEd	0.006	0.002	0.003

CD (p = 0.05)	NS	NS	NS

Fig 1. Effect of paper board industry effluent on macronutrient uptake (g plant⁻¹) in bitter gourd

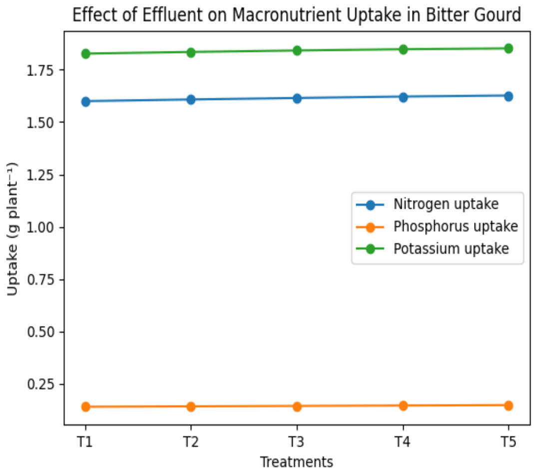
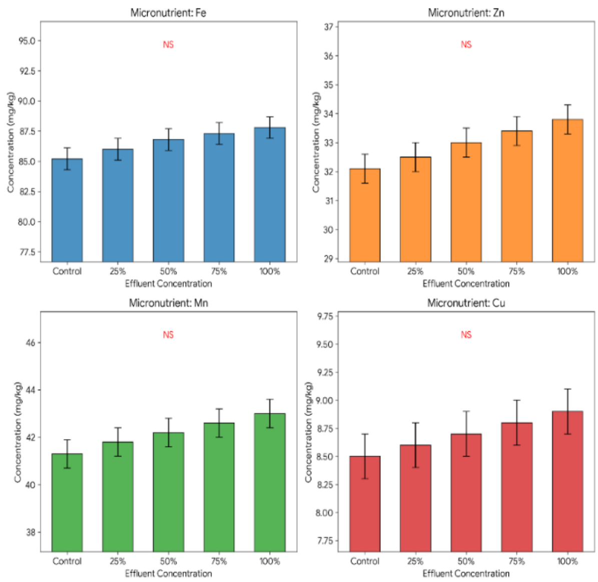


Fig 2. Effect of paper board industry effluent on micronutrient content (mg kg⁻¹) in bitter gourd



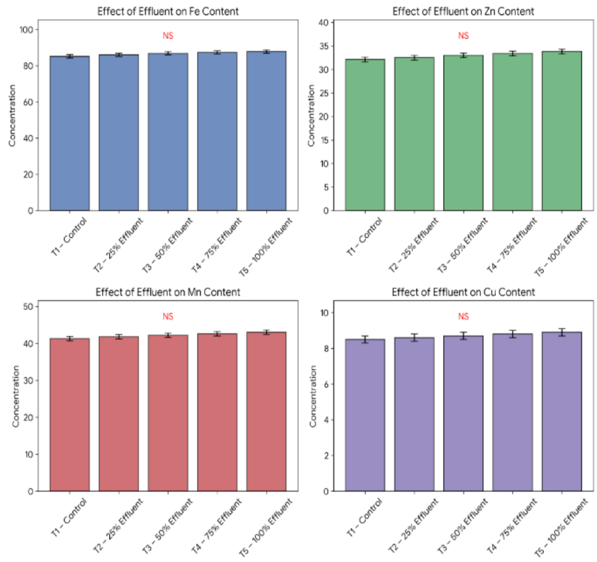


Table 3. Heavy metal concentration (mg kg⁻¹) in bitter gourd under effluent irrigation

Treatment	Cd	Ni	Cr	Pb
T_1 - Control	BDL	BDL	BDL	BDL
T_2 - 25% Effluent	BDL	BDL	BDL	BDL
T_3 - 50% Effluent	BDL	BDL	BDL	BDL
T_4 - 75% Effluent	BDL	BDL	BDL	BDL
T_5 - 100% Effluent	BDL	BDL	BDL	BDL

BDL - Below Detectable Limit

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