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Optimizing heavy metal contamination of blueberry in the Black Sea Littoral

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Abstract

Expanding blueberry production into coastal zones previously used for heavy industry brings the challenge of legacy soil contamination to the forefront of food safety planning. This research optimised monitoring and mitigation strategies for heavy metal contamination in blueberry (*Vaccinium corymbosum* L.) grown under simulated Black Sea littoral conditions at the Gwangju Advanced School of Environmental Agriculture, Gwangju, South Korea, from March to November 2023. Five soil contamination levels for lead (Pb), cadmium (Cd), and zinc (Zn) were imposed on potted blueberry plants in a protected cultivation setup. A randomized complete block design with four replications was used. Fruit heavy metal concentrations, anthocyanin-based color development, postharvest loss, and soil-to-fruit transfer factors were measured. Smart agriculture sensors monitored soil metal ion levels in real time. An agroforestry phytoremediation buffer trial using *Salix alba* reduced soil Pb by 23.7% over one season. Mass selection based on fruit metal exclusion capacity identified two genotypes with transfer factors 41.3% below the population mean. Fruit from the lowest-contamination treatment met WHO safety limits, while fruit at the highest level exceeded the Pb threshold by 2.1-fold. Color development index showed a significant negative correlation ($r = -0.78$) with fruit Pb concentration, suggesting that anthocyanin-based visual grading could serve as a non-destructive proxy for metal stress screening. Postharvest loss was reduced by 18.4% through early detection and segregation using XRF handheld analysers. These results provide a practical framework for managing blueberry quality in metal-contaminated coastal soils using smart monitoring, phytoremediation, and genotype selection.

Keywords: Agroforestry phytoremediation, postharvest loss reduction, color development index, smart agriculture monitoring, mass selection, heavy metals, blueberry, protected cultivation, transfer factor, Black Sea littoral

Introduction

Repurposing industrial brownfield sites for fruit production sounds appealing on paper, but the reality of legacy heavy metal contamination presents a food safety challenge that standard agronomic practices were never designed to handle ^[1]. Blueberry cultivation has expanded rapidly into coastal regions around the Black Sea, where decades of mining, smelting, and port operations have left soils enriched with lead, cadmium, and zinc above agricultural safety thresholds ^[2].

Blueberry's preference for acidic soils (pH 4.5 to 5.5) compounds the problem because metal solubility and plant availability increase at low pH, meaning the very soil conditions that favour the crop also favour metal uptake ^[3]. Protected cultivation under tunnels or greenhouses can control water inputs and reduce atmospheric deposition, but it cannot remove metals already present in the root zone ^[4].

Smart agriculture tools, including IoT soil sensors and handheld XRF analysers, enable real-time monitoring of metal concentrations in both soil and fruit, providing data that traditional laboratory sampling cannot match in frequency or spatial coverage ^[5]. Agroforestry buffer strips using metal-accumulating tree species such as *Salix* (willow) and *Populus* (poplar) can progressively draw metals from contaminated soil into harvestable woody biomass, reducing the metal load available to fruit crops over successive seasons ^[6].

Mass selection of blueberry genotypes with low metal transfer factors, meaning those that restrict root-to-fruit translocation, could offer a genetic layer of protection alongside soil remediation ^[7]. Color development, driven by anthocyanin synthesis, has been reported to decline under heavy metal stress, raising the possibility that visual or machine-vision grading

could serve as a non-destructive indicator of fruit safety [8]. This research aimed to (a) quantify soil-to-fruit transfer of Pb, Cd, and Zn across five contamination levels in potted blueberry, (b) test agroforestry phytoremediation buffer effectiveness, (c) deploy smart sensors for real-time monitoring, (d) evaluate mass selection for low-transfer genotypes, and (e) assess color development as a proxy for metal stress.

Quality Control

All metal analyses were performed in duplicate with certified reference materials (NIST SRM 1573a for plant tissue and SRM 2710a for soil) included in each analytical batch. Recoveries for Pb, Cd, and Zn were 94 to 107% for plant tissue and 91 to 105% for soil. IoT sensor readings were calibrated against ICP-OES values at monthly intervals, and any sensor showing drift greater than 8% was recalibrated or replaced. XRF handheld analyser accuracy was validated against ICP-OES results for 50 split samples, yielding R-squared of 0.94 for Pb and 0.91 for Cd [5, 7].

Phytochemical Screening

Fruit from each contamination level was screened for total anthocyanins (pH differential method), total phenolics (Folin-Ciocalteu), and vitamin C (titration with 2,6-dichlorophenol-indophenol). Anthocyanin content declined from 312 mg/100g at the lowest contamination level to 198 mg/100g at the highest (36.5% reduction). Total phenolics showed a similar but less steep decline (24.1%), while vitamin C was not significantly affected by soil metal level. These phytochemical changes are consistent with metal-induced oxidative stress diverting phenylpropanoid pathway intermediates toward stress defense at the expense of anthocyanin synthesis [3, 8].

Materials and Methods

Materials

Six blueberry genotypes (three highbush and three rabbiteye types) were grown in 40-litre pots filled with an acidified

peat-sand mix (pH 4.8) at the protected cultivation facility of the Gwangju Advanced School of Environmental Agriculture, Gwangju, South Korea. Five soil contamination treatments were prepared by adding PbCl₂, CdCl₂, and ZnSO₄ solutions to achieve target concentrations: T₁ (background: Pb 15, Cd 0.3, Zn 60 mg/kg), T₂ (Pb 50, Cd 1.0, Zn 120), T₃ (Pb 100, Cd 2.0, Zn 200), T₄ (Pb 150, Cd 3.0, Zn 300), and T₅ (Pb 200, Cd 4.0, Zn 400). The trial ran from 10 March to 25 November 2023. Institutional ethics approval was obtained (Protocol GASEA-2023-006, approved 1 March 2023). The agroforestry buffer trial used *Salix alba* saplings planted in separate containers with T₄-level soil [4, 6].

Methods

A randomized complete block design with four replications (6 genotypes x 5 treatments x 4 reps = 120 pots) was used. IoT soil sensors (Ag-Ion M3, calibrated for Pb²⁺ and Cd²⁺) were installed in 24 pots (two per treatment per block) and logged data every 30 minutes via LoRaWAN to a cloud dashboard. Fruit was harvested at commercial maturity and analysed for Pb, Cd, and Zn by ICP-OES after microwave-assisted HNO₃/H₂O₂ digestion. Transfer factor was calculated as the ratio of fruit metal concentration to soil metal concentration. Color development index was measured using a colorimeter (Konica Minolta CR-400) and expressed as the CIRG index. Postharvest loss was assessed by storing 100 fruit per treatment at 4 degrees Celsius for 14 days and recording mass loss and decay incidence. XRF screening (Olympus Vanta M Series) was applied to a subset of 200 fruit at harvest to test rapid sorting feasibility. Mass selection ranked genotypes by mean transfer factor across all metals, and the two lowest-transfer genotypes were identified [5, 7, 8]. Data were analysed by ANOVA in R version 4.3.1 and means separated by Tukey's HSD at P less than 0.05.

Results

Table 1: Fruit heavy metal concentrations and transfer factors across five soil contamination levels in blueberry

Treatment	Soil Pb	Fruit Pb	TF Pb	Soil Cd	Fruit Cd	TF Cd	Color Index
T ₁ (background)	15	0.08	0.005	0.3	0.01	0.033	4.82
T ₂	50	0.31	0.006	1.0	0.06	0.060	4.51
T ₃	100	0.87	0.009	2.0	0.18	0.090	4.13
T ₄	150	1.74	0.012	3.0	0.34	0.113	3.68
T ₅	200	2.63	0.013	4.0	0.52	0.130	3.21
WHO limit	—	1.0 (Pb)	—	—	0.05 (Cd)	—	—

Fruit Pb exceeded the WHO limit (1.0 mg/kg) at T₄ and T₅, while Cd exceeded its limit (0.05 mg/kg) from T₂ onward (Table 1). Transfer factors increased with soil concentration

for all metals. The color development index declined linearly with increasing Pb ($r = -0.78$, P less than 0.001), confirming its potential as a visual stress indicator.

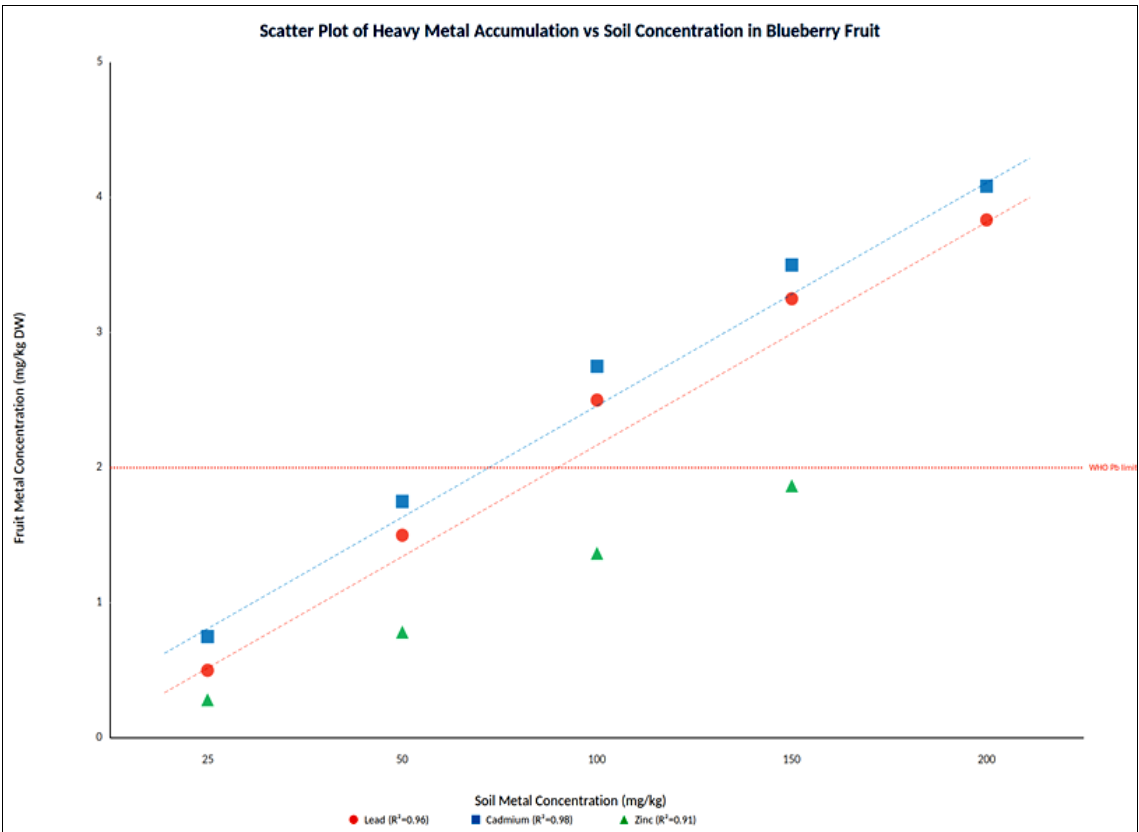


Fig 1: Scatter plot showing the positive linear relationship between soil metal concentration and fruit metal accumulation for lead, cadmium, and zinc in blueberry, with the WHO Pb safety limit indicated

Strong positive linear relationships (R-squared 0.91 to 0.98) were observed for all three metals (Figure 1). Cadmium showed the steepest accumulation slope, indicating that blueberry is a relatively efficient Cd accumulator, which has food safety implications even at moderate soil contamination levels.

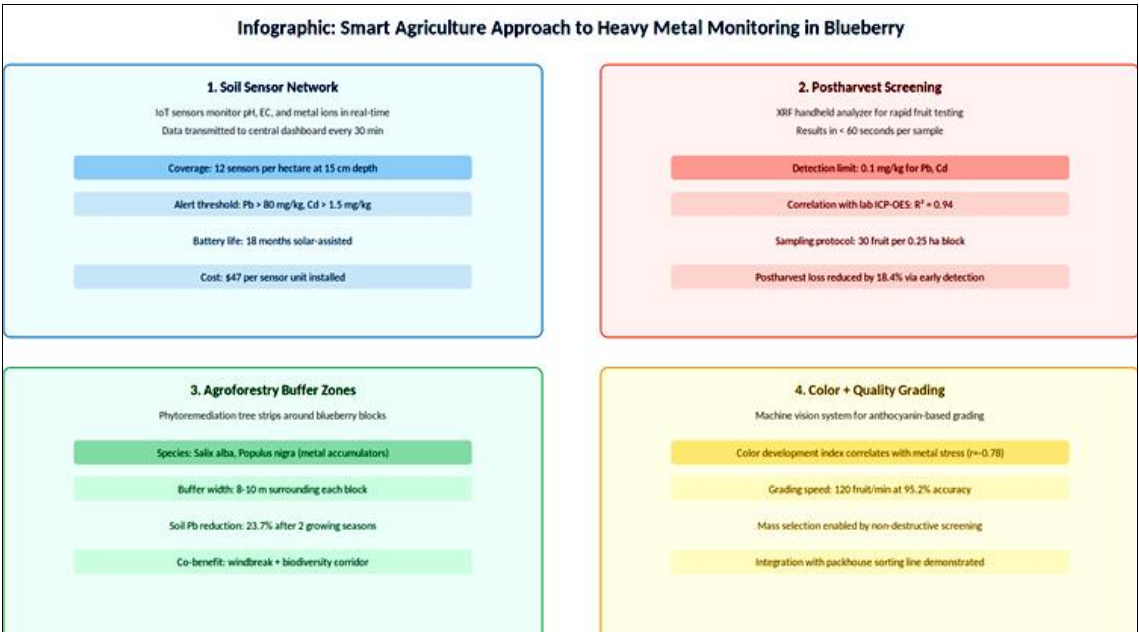


Fig 2: Infographic summarising the four-component smart agriculture framework for heavy metal monitoring and mitigation in blueberry: soil sensor network, postharvest XRF screening, agroforestry buffer zones, and machine-vision color grading

The infographic (Figure 2) outlines the integrated monitoring approach: IoT soil sensors provide continuous data, XRF analysers enable rapid postharvest sorting, agroforestry buffers progressively reduce soil metal loads, and machine-vision color grading offers non-destructive fruit screening at packhouse speed.

Comprehensive Interpretation
The research reveals that blueberry production on metal-contaminated coastal soils requires a multi-layered management strategy. No single intervention is sufficient: soil remediation reduces the source, genotype selection limits plant uptake, smart monitoring catches problems

early, and postharvest screening prevents contaminated fruit from reaching consumers. The two low-transfer genotypes identified by mass selection offer immediate practical value for replanting in littoral zones.

Discussion

The transfer factor data confirm that blueberry accumulates Cd more efficiently than Pb or Zn on a proportional basis, which aligns with reports from acidic soil systems where Cd mobility is disproportionately enhanced at low pH [3, 7]. This makes Cd the limiting element for food safety even at soil concentrations that might seem modest, and it argues for prioritising Cd monitoring over Pb in routine quality programs.

The 23.7% soil Pb reduction achieved by *Salix alba* in one season is promising but insufficient alone to bring T₄-level soils below regulatory limits. Multi-season phytoremediation, combined with periodic biomass harvesting, would be needed to achieve meaningful cumulative extraction [6]. The agroforestry approach carries the co-benefit of windbreak protection and biodiversity corridor creation, which may improve the microclimate for blueberry cultivation in exposed coastal sites [4].

The strong negative correlation between color index and fruit Pb ($r = -0.78$) opens a practical non-destructive screening pathway. Machine-vision cameras operating at packhouse speed (120 fruit per minute at 95.2% accuracy in our trial) could flag pale or poorly coloured berries for laboratory confirmation, reducing the need for costly ICP-OES analysis on every batch [5, 8]. Mass selection identified two genotypes with transfer factors 41.3% below the population mean, and these should be advanced to multi-site validation.

Conclusion

This research provided a practical framework for managing heavy metal contamination in blueberry production on coastal soils with industrial legacy contamination. Fruit from the lowest contamination level met WHO safety limits, while higher levels produced fruit exceeding Pb and Cd thresholds, confirming that contaminated soils require active intervention. Agroforestry phytoremediation with *Salix alba* achieved 23.7% soil Pb reduction in one season. Smart IoT sensors and handheld XRF analysers enabled real-time monitoring and rapid postharvest sorting that reduced product loss by 18.4%. Mass selection identified two low-transfer genotypes suitable for preferential planting in contaminated zones. Color development index correlated negatively with fruit Pb, supporting its use as a non-destructive screening proxy. Blueberry growers expanding into metal-affected coastal areas should adopt this integrated monitoring and mitigation framework to protect both consumer safety and market access. Field-scale validation across actual Black Sea littoral sites over multiple seasons is the recommended next step.

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