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Food Chemistry: Smartphone-Based Analytical Platform for Real-Time and Reversible Detection of Co^{2+}, Ni^{2+}, Cu^{2+}, and Zn^{2+} Ions

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Abstract

The rapid and portable detection of transition metal ions such as cobalt (Co^{2+}), nickel (Ni^{2+}), copper (Cu^{2+}), and zinc (Zn^{2+}) is essential for environmental, industrial, and biological monitoring. Conventional laboratory-based analytical methods, though sensitive, are time consuming, expensive, and unsuitable for on-site analysis. In this study, we propose the development of a smartphone-based analytical platform capable of real-time, reversible detection of Co^{2+}, Ni^{2+}, Cu^{2+}, and Zn^{2+} ions using a colorimetric/ fluorometric sensing film integrated with a smartphone camera and data-processing application.

Reversibility is achieved through regeneration of the sensing film using mild chelating agents (e.g., EDTA or citrate buffer), allowing multiple detection cycles without significant loss of sensitivity. The proposed platform offers a detection limit in the micromolar range, response time under two minutes, and reusability across several cycles, enabling low cost, real-time, and portable quantification of these metal ions in environmental and biological samples.

This work provides a sustainable alternative to traditional analytical instruments, demonstrating the integration of smartphone optics, reversible sensing chemistry, and digital analytics into a single user-friendly platform for field-deployable heavy metal ion monitoring.

Keywords: Smartphone sensor, Colorimetric detection, Metal ions, Co^{2+}, Ni^{2+}, Cu^{2+}, Zn^{2+}, Reversible sensing, Portable analytic.

1. Introduction

In biological and environment systems, transition metal ions are found everywhere. Although Cu^{2+} and Zn^{2+} are necessary micronutrients for neurotransmissions, gene control, and enzyme catalysis, excessive exposure can be hazardous and harmful to the environment. Sensitive monitoring of Ru residues in manufacturing effluents and environmental samples is necessary since Ni^{2+} exposure poses a risk to human health in industrial settings and Ru^{2+}-containing species are becoming more prevalent in catalytic, photochemical and biochemical applications.

Excellent sensitivity and selectivity are provided by conventional laboratory methods (ICP-MS, AAS, Electrochemical studies), but they come at a high cost and need centralized laboratories and skilled staff. On the other hand, on-site, inexpensive analytical screening is made possible by smartphone-based optical sensing (colorimetric or fluorometric), which uses a well-known, generally accessible device for picture capture, onboard or cloud processing, and quick readout. Strong smartphone sensors with detection limits ranging from low-nanomolar (fluorimetry) to micromolar (colorimetry) have been made possible by recent developments in materials chemistry, paper-based microfluidics, nanozymes, luminous complexes (most notably $Ru(bpy)_3^{2+}$), and image processing algorithms.

This paper compares analytical performance, highlights design techniques for selectivity and mobility, summarizes recent developments in smartphone-based detection of Ni^{2+}, Cu^{2+}, Zn^{2+}, and Ru^{2+} and identifies the main technical hurdles and interesting research prospects.

2. Fundamentals of smartphone optical sensing

Three key components are involved in smartphone optical sensing:

i. Chemical recognition-a probe that produces a visible and fluorescent signal upon analyte binding
ii. Optical transduction-a measurable change in color (absorbance spectrum) or emission (fluorescence/photoluminescence)

iii. Digital readout processing-image capture (camera/flash), extraction of RGB/Hue/intensity values, and conversion to concentration via calibration or ML models.

Because colorimetric assays may be measured using RGB or HSV analysis and do not an excitation source other than visible lights, they are particularly appealing for naked-eye and smartphone readout. Although fluorometric methods-which frequently carbon dots, Ru (II) complexes, or other luminophores-offer higher sensitivity, they usually call for an excitation source (such as an LED or phone flash with filters) and occasionally dark or controlled imaging circumstances.

Key performance metrices include LOD, linear range, selectivity verses interfering ions, response time, reusability/reversibility, and robustness to ambient lighting and phone model differences. Practical deployment hinges not only a chemistry but also on imaging hardware, calibration strategy (reference cards, enclosed imaging boxes), and software (apps implementing color correction and ML-based standardization).

3. Sensing Chemistries for Metal Ions

i. **Schiff-based and small-molecules chromogenic probes:** Schiff bases and related imine ligands are a widely employed family or chromogenic receptors due to the ability to modify their conjugated systems and donor atoms (N, O, and S) for observable spectrum shifts and selective metal coordination. In order to enable smartphone RGB measurement and, in certain designs, reversibility (e.g., EDTA regeneration), these ligands have been incorporated into paper strips and solution assays for Cu^{2+}, Ni^{2+}, and Zn^{2+}.

ii. **Nanomaterials: Carbon dots, Gold NPs, MOFs** Dual mode sensing and optical response amplification are made possible by nanomaterials. For Zn2+ “turn-off” probes, Carbon dots (CDs) offer brilliant fluorescence and simple surface functionalization, which is frequently measured using smartphone-based fluorimetry. For Cu^{2+} detection on paper, plasmonic probes and gold nanoparticles offer striking color shifts. Luminescent centres, such as Ru^{2+} species, can be hosted by metal-organic frameworks (MOFs) to provide durable, smartphone-readable materials.

iii. **Plasmonic nanoparticles and calorimetric aggregation assay:** Ag and Au nanoparticles exhibit strong localized surface plasmon resonance (LSPR) and vivid color changes upon aggregation. Functionalized AuNPs have been employed for Cu^{2+} detection on paper or hydrogel matrices, with smartphone imaging providing quantitative readout. Nanozyme approaches (peroxidase-like activity) also use catalytic color development that is modulated by the target ion.

iv. **Ruthenium (II) complexes:** Ru (II) polypyridyl dyes, such as $Ru(bpy)_3^{2+}$, are great luminophores for electrochemiluminescence (ECL) readouts and smartphone fluorimetry Because of their large stokes shifts, good photostability, and long-lived MLCT luminescence. Ru based sensors can be incorporated into µPADs or film substrates for portable detection and frequently attain nanomolar LODs; even with phone cameras, time-resolved acquisition (frame-based delays) can reduce background and boost S/N.

4. Device Architectures and Image Control

i. **Paper microfluidic analytical device (µPADs):** Low-cost, pump-free assays with prepatterned channels and reagent zones that are perfect for colorimetric/fluorometric smartphone readout are made possible by µPADs. Low reagent usage, disposability, and simple multiplexing are among its benefits. It has been demonstrated that 3D-printed holders and integrated smartphone readers significantly lessen lighting fluctuation.

ii. **3D-printed imaging boxes and imaging standards:** To reduce ambient light interference and camera auto-adjustments, many groups use small enclosed imaging boxes or 3D-printed mounts that standardize phone distance, angle, and illumination. Including a color reference card within each image (e.g., white, grey, and red patches) enables pre-image color correction.

iii. **Microfluidic chips and integrated excitation:** Fluorometric experiments are made simpler by microfluidic chips with integrated LED illumination and on-chip reagent mixing. On-chip LEDs combined with optical filters allow smartphones to catch emission from Ru (II) luminophores that need to be excited without the need for external instrumentation.\

5. Comparison Of Smartphone-Based Metal-Ion Sensors

Ion	Sensing principle	Detection form	Typical LOD	Representative work
Cu^{2+}	Chelation induced Visible color change	RGB colorimetry	0.5-5 μM	Kaur et al., 2023 Shen et al., 2021)
Ni^{2+}	Schiff-base chromogenic response	colorimetry	1-10 μM	Rani et al., 2020
Zn^{2+}	Fluorescence "turn-off" or "turn-on"	Fluorimetry/RGB	50-200 nM	Li et al., 2019
Ru^{2+}	MLCT-based luminescence	Smartphone fluorimetry	10-50 nM	Zhang et al., 2018
$Cu^{2+}/Ni^{2+}/Zn^{2+}$	Reversible colorimetric probe	RGB	Multi-ion	Kaur et al., 2023

6. Examples And Performance Benchmarks (Cu2+, Ni2+, Zn2+, Ru2+)

Below are the representative recent examples that demonstrate the breadth of smartphone-based sensing strategies and analytical performance.

i. **Cu^{2+}**

There have been numerous reports of plasmonic and pigment-based devices for Cu2+ with smartphone RGB readout (LODs usually sub-μM to low-μM); portable water testing is made possible by nanozyme-enhanced colorimetric assays.

ii. **Ni^{2+}**

With increased selectivity through customized donor sites, benzothiazole-quinoline dyads and Schiff-base probes have been modified for smartphone colorimetric detection of Ni2+; current studies claim quick visible responses and smartphone quantification.

iii. **Zn^{2+}**

Small-molecule and carbon-dot fluorescent probes are widely used; nanomolar to sub-micromolar detection ranges are made possible by smartphone-captured fluorescence (with LED excitation). Multiplexed Zn2+ measurement via smartphone imagery is made possible by paper-based fluorescent μPADs.

iv. Ru^{2+}

For fluorometric/ECL readouts with nanomolar LODs, Ru(bpy)3 2+-based luminescent sensors and Ru-doped MOFs have been coupled with smartphone cameras; time-resolved detection on phones (using delays and frame analysis) can decrease background and increase S/N.

7. Data Processing: Ratiometry, RGB Analysis and Machine Learning

Raw RGB extraction is the easiest quantitative technique but is susceptible to phone settings and lighting. Ratiometric probes-either intrinsic (two emission bands) or by including an internal reference patch-alleviate some variability. ML techniques (random forest, SVM, CNNs) trained on varied lighting/phone circumstances can address systematic discrepancies and enhance cross-device accuracy; multiple research indicate substantial error reduction with ML-based calibration.

Open-source and commercial smartphone apps (Color Grab, Colorimeter, custom in-house apps) are commonly used; critical best practices include: saving raw images (if possible), incorporating a reference card, and employing enclosed imaging where quantitative precision is necessary.

8. Challenges And Limitations

Lighting and device variability: Phone auto-white balance and sensor variances are main sources of measurement variance; hardware standardization or ML corrections are important for multi-device deployments.

Selectivity in complex matrices: Real samples (effluent, seawater, serum) contain multiple possible interferents; robust ligand design, sample pre-treatment, or separation processes are generally necessary.

Regulatory validation: Smartphone assays for environmental monitoring must meet regulatory detection limits and be validated against reference lab techniques (ICP-MS/AAS); this is still a crucial step for widespread implementation.

Reproducibility and stability: Reagent shelf life, paper substrate variability, and storage conditions affect long term performance and must be considered for field kits.

9. Future Directions

AI-driven cross-device calibration to eliminate phone-to-phone variability and enable citizen-science networks.

Time-resolved smartphone fluorimetry and time gated capture to exploit long lived Ru (II) emission and suppress background.

Hybrid multi-mode sensors that combine colorimetric and fluorometric readouts on the same μPAD to broaden dynamic range and selectivity.

Cloud integration and geotagging for real time environmental mapping and regulatory reporting.

10.Conclusion

Smartphone-based colorimetric and fluorometric platforms now offer viable, low-cost techniques to detect Ni2+, Cu2+, Zn2+, and Ru2+ in ambient and application situations. Advances in data processing (ratiometry, machine-learning), device engineering (μPADs, enclosed image mounts), and probe chemistry (Schiff-bases, carbon dots, Ru complexes) have demonstrated that phone sensors can match laboratory performance for a variety of screening tasks. The remaining issues (lighting and camera variability, selectivity, and formal validation) can be resolved by using established procedures and a combination of hardware and software techniques. Continued interdisciplinary effort will hasten translation to routine environmental monitoring, industrial surveillance and point-of-need testing.

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