

Assessment of Multi-Metal Pollution in Aby Lagoon Sediments (Côte d'Ivoire): An ICP-MS Geochemical Approach

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Abstract

This study assesses the contamination of sediments in Aby Lagoon, specifically in the Étuessika-Assinie Canal sector, by trace metals (Cd, Ni, Pb, Hg, Zn, As, Cr, Cu). ICP-MS analyses reveal concentrations far exceeding the geochemical background values of the upper continental crust (UCC), confirming severe pollution. Maximum levels reached 52.19 mg/kg for cadmium (Cd), 453.20 mg/kg for nickel (Ni), and 1186.99 mg/kg for lead (Pb). Geochemical indices (enrichment factor, geoaccumulation index) suggest contamination of predominantly anthropogenic origin, probably linked to artisanal gold mining as well as agricultural and urban discharges. Ecotoxicological assessment highlights a high risk for benthic organisms and a potential threat to local populations.

Keywords

Aby Lagoon, Sediments, Heavy Metals, Contamination, Ecotoxicology, Côte d'Ivoire

1. Introduction

Coastal lagoon ecosystems represent dynamic interfaces between continental and marine environments. They are characterized by high biological productivity and hold major socio-economic importance for riparian populations (Anthony et al., 2014). However, these ecosystems are increasingly subjected to anthropogenic pressures, notably artisanal gold mining, intensive agriculture, and domestic discharges, which promote the accumulation of heavy metals in sediments (Ouattara et al., 2021).

In Côte d'Ivoire, several recent studies confirm this trend. [Yapi et al. \(2025\)](#) reported concerning concentrations of mercury (Hg), arsenic (As), lead (Pb), and cadmium (Cd) in Aby Lagoon, with potential health risks associated with dermal contact. Similarly, [Kouame et al. \(2025\)](#) highlighted non-carcinogenic risks in Ébrié Lagoon linked to the consumption of Tilapia contaminated by mercury (Hg) and lead (Pb). In Fresco Lagoon, [Ouattara et al. \(2020\)](#) revealed moderate to severe anthropogenic pollution by lead (Pb), arsenic (As), and zinc (Zn), attributed to urban and agricultural activities. At the African scale, [Shetaia et al. \(2025\)](#) demonstrated that lagoons in the Nile Delta remain heavily contaminated by heavy metals, even after hydrological regulation by the Aswan Dam.

Aby Lagoon, located in southeastern Côte d'Ivoire, exemplifies this issue. The Etuessika-Assinie Canal sector, in particular, receives contaminated sediment inputs from the Bia and Tanoé watersheds, where artisanal gold mining is rapidly expanding. In this context, the present study aims to characterize the geochemical composition of bottom sediments using inductively coupled plasma mass spectrometry (ICP-MS), in order to assess contamination levels by trace metals and compare these concentrations with upper continental crust (UCC) background values ([Wedepohl, 1995](#)).

2. Methodology

2.1. Description of the Study Area

The locality of Etuésika is located in southeastern Côte d'Ivoire, within the Adiaké department (Sud-Comoé region). Situated on the southern shore of Aby Lagoon, the local population relies primarily on artisanal fishing, subsistence farming, and beach tourism. Aby Lagoon, the focus of this study, is one of the largest lagoon systems in the country. It covers an area of approximately 424 km² with an average depth of 4.82 m. This lagoon ecosystem, rich in mangroves, also hosts the Ehotilé Islands National Park.

Aby Lagoon is connected to the Atlantic Ocean through the Assinie Canal, which was artificially opened in 1942. The opening of this canal profoundly altered the ecological functioning of the lagoon system, transforming the originally brackish environment into a dynamic estuarine system influenced by marine inputs. Tidal currents entering through the canal affect circulation and sedimentation several kilometers inside the lagoon ([Wango et al., 2013](#)).

During the rainy season, riverine inputs are at their maximum, leading to significant freshening of the lagoon waters. Conversely, in the dry season, reduced river discharge favors the intrusion of marine waters through the canal, resulting in elevated salinity levels ([Kouamenan et al., 2019](#)). The Etuessika-Assinie Canal sector constituted the study area. The investigation focused on the geochemical characterization of bottom sediments, based on four sampling points (ETUc-01 to ETUc-04), as shown in [Figure 1](#). The geographic coordinates of these sampling stations are presented in [Table 1](#).

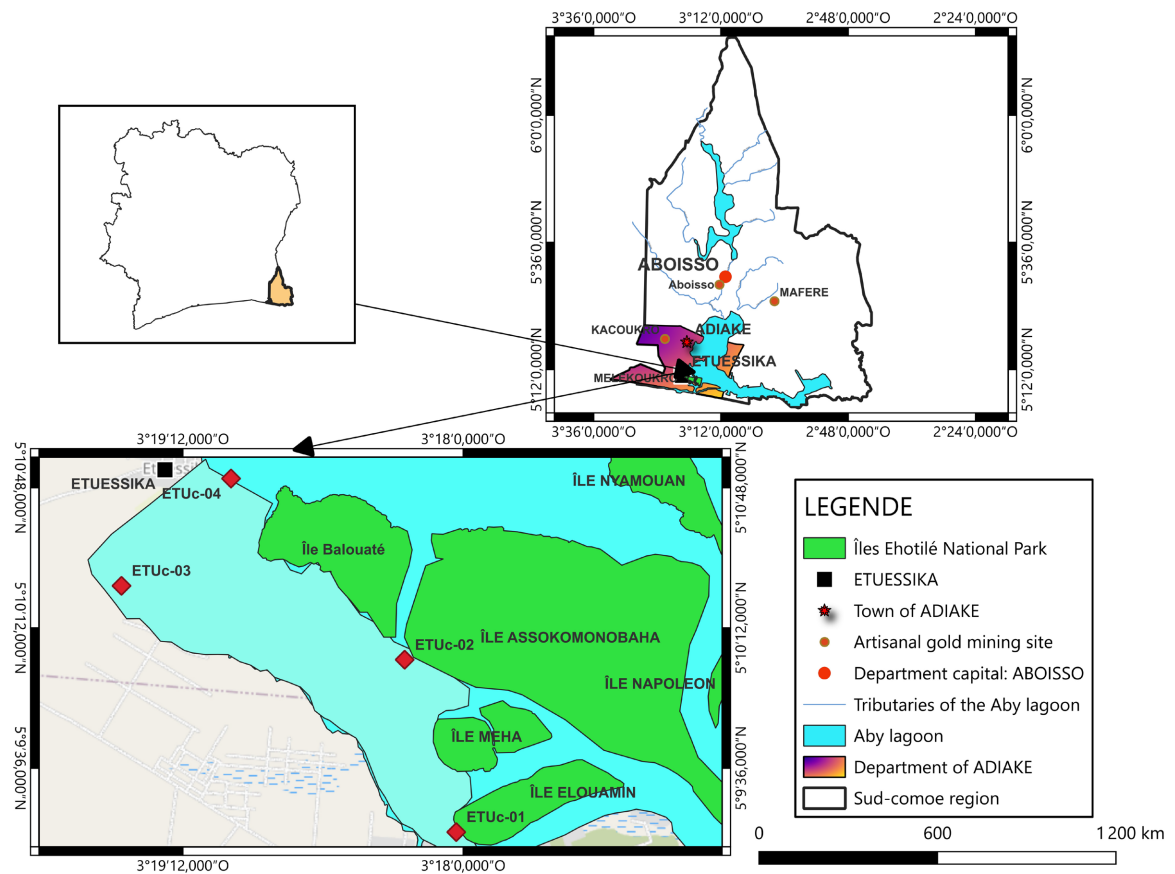


Figure 1. Location map of the study area.

Table 1. Geographical coordinates of sampling points.

Sample point	Longitude (X)	Latitude (Y)
ETUc-01	03° 18'01.79"W	05° 09'19.58"N
ETUc-02	03° 18'15.04"W	05° 10'03.84"N
ETUc-03	03° 19'27.76"W	05° 10'22.8"N
ETUc-04	03° 18'59.62"W	05° 10'50.35"N

The selection of the four sampling points was guided by the hydrological dynamics of the lagoon and the human activities in its immediate surroundings. The first point is located at the junction of the Assinie Canal and the Aby Lagoon, at the interface with the Atlantic Ocean. The second crosses the area of the central lagoon islands. The third, situated near residential areas, reflects the interaction between the natural environment and human activities. Finally, the fourth point marks the eastern boundary of the study area.

2.2. Methods

Sampling was carried out from August 7 to 8, 2025 using a piston corer measuring 3 m in length and 4 cm in diameter. The cores, each 30 cm long, were measured

and subsequently subdivided into regular intervals of 10 cm. Each horizon was preserved in sterile, labeled plastic bags.

The next step involved sediment pretreatment, including drying at 60°C, grinding, and sieving. Acid digestion was then performed (HCl/HNO₃ in a closed microwave system), followed by ICP-MS analysis, which enabled precise quantification of trace metals (TMs) at very low concentrations. The quality control protocol was applied by the laboratory to ensure the reliability of the ICP-MS measurements. It included the use of certified reference materials to verify the accuracy of concentrations, the regular insertion of procedural blanks to monitor potential contamination, and duplicate analyses to assess reproducibility. Recovery rates were checked through the addition of standard solutions, while detection limits (LOD) and quantification limits (LOQ) were systematically established for each element. Results below the LOQ were reported as “< LOQ” in accordance with standard recommendations. Concentrations were calculated (Equation (1)) according to the following relation:

$$D = \frac{(A - T) \times B}{C} F \quad (1)$$

where:

D: represents the concentration expressed in mg/kg;

A: concentration of the metal in the analyzed solution (mg/L);

T: concentration of the metal in the blank (mg/L);

B: final volume of the sample (mL);

C: dry weight of the sample used (g);

F: dilution factor, if applicable.

Geochemical indices were then calculated and compared with upper continental crust (UCC) background values (Wedepohl, 1995). These include:

Enrichment factor (EF) (Equation (2)), normalized to aluminum, which qualifies the degree of contamination (from negligible to extremely high)

$$EF = (Cx/Cref)_{\text{sample}} / (Cx/Cref)_{\text{background}} \quad (2)$$

where:

C_x: concentration of the studied element (e.g., As, Pb, Zn, Cu) in the sediment sample;

C_{ref}: concentration of the reference element (commonly Al, Fe, Ti, or Sc), chosen because it is stable and minimally affected by human activities;

(*C_x/C_{ref}*): sample ratio of the studied element to the reference element in the analyzed sample;

(*C_x/C_{ref}*): ratio of the studied element to the reference element in the geological background.

Here is the commonly used classification of the enrichment factor (EF) according to Sutherland (2000). This classification (Table 2) is widely applied in environmental geochemistry to distinguish between natural background levels and anthropogenic contamination.

Table 2. Classification of the enrichment factor (EF).

EF Value	Interpretation
EF < 2	Minimal enrichment (element mainly of natural origin)
2 ≤ EF ≤ 5	Moderate enrichment
5 ≤ EF ≤ 20	Significant enrichment
20 ≤ EF ≤ 40	Very high enrichment
EF > 40	Extremely high enrichment

The geoaccumulation index (Igeo) (Equation (3)) is based on the ratio between measured concentrations and background values, classifying sediments from unpolluted to extremely polluted:

$$I_{geo} = \log^2 \left[\frac{C_n}{(1.5 \times B_n)} \right] \quad (3)$$

where:

C_n : measured concentration of element n ;

B_n : background concentration of element n (UCC values);

The constant 1.5 accounts for natural variability in background values.

The geoaccumulation index (Igeo) is interpreted in **Table 3**.

Table 3. Classification of the geoaccumulation index (Igeo).

Igeo Value	Pollution Degree
Igeo < 0	Geochemical background
1 ≤ Igeo < 2	Unpolluted to slightly polluted
2 ≤ Igeo < 3	Slightly to moderately polluted
3 ≤ Igeo < 4	Moderately polluted
4 ≤ Igeo < 5	Strongly polluted
Igeo ≥ 5	Extremely polluted

The mean effect range quotient (Mean-ERQ) (Equation (4)), following **Macdonald et al. (2000)** (**Table 4**), was first calculated individually for each metal using the ecotoxicological thresholds TEC and PEC. The values obtained were then averaged for each sample to provide an integrated risk estimate at the station level. Station-level probabilities of biological effects were derived from these averaged Mean-ERQ values, according to the standard interpretation grid (Mean-ERQ < 0.5: rare effects; 0.5 - 1.5: occasional effects; 1.5 - 2.3: frequent effects; >2.3: probable effects). The threshold applied in this brackish lagoon was selected in the absence of local sediment quality guidelines, relying instead on internationally recognized criteria (TEC/PEC). Consequently, the risk categories presented here should be considered as a preliminary assessment, offering an initial framework for ecological interpretation and environmental management.

$$\text{Mean-ERQ} = \frac{\left[\left(\frac{C_m}{TEC} \right) + \left(\frac{C_m}{PEC} \right) \right]}{2} \quad (4)$$

where:

C_m : measured concentration of the metal;

TEC : threshold effect concentration;

PEC : probable effect concentration.

Table 4. TEC and PEC values in mg/kg (MacDonald et al., 2000).

Trace Metal Element	TEC (Threshold Effect Concentration)	PEC (Probable Effect Concentration)
As	9.79	33.0
Cd	0.99	4.98
Cr	43.4	111.0
Cu	31.9	149.0
Hg	0.18	1.06
Ni	22.7	48.6
Pb	35.8	128.0
Zn	121.0	459.0

3. Results

3.1. Sediment Lithology

The lithological description of the cores reveals four distinct facies:

- 1) Organic fluid muds, dark gray to black in color (5Y 2/1 to 10YR 2/1), very rich in organic matter and characterized by a strong odor, observed at stations ETUc-01 and ETUc-02;
- 2) Fine muddy sands with abundant shell fragments (bivalves and gastropods), beige to light brown in color (2.5Y 5/2 to 10YR 5/3), identified at station ETUc-03;
- 3) Grayish compact muds (5Y 4/1), containing partially decomposed plant debris, described at station ETUc-04.

3.2. Trace Metal Concentrations

ICP-MS analyses would reveal particularly high concentrations of cadmium (Cd), lead (Pb), nickel (Ni), and mercury (Hg), far exceeding upper continental crust (UCC) background values. In contrast, zinc (Zn), copper (Cu), and chromium (Cr) would show moderate levels, while iron (Fe) and aluminum (Al) would primarily reflect lithogenic origin. Cadmium (12.52 - 52.19 mg/kg) would largely exceed the background value (0.1 mg/kg), suggesting massive anthropogenic pollution. Lead (10.16 - 1186.99 mg/kg), with a peak at ETUc-01 (10 - 20 cm), would reflect acute contamination possibly from urban and industrial discharges. Nickel (38.17 - 453.20 mg/kg) would indicate both lithological influence and anthropogenic inputs, while mercury (1.035 - 27.483 mg/kg; maximum at ETUc-02) would

confirm severe contamination likely linked to artisanal gold mining. Zinc (381 - 9652 mg/kg), copper (84 - 621 mg/kg), and chromium (48 - 279 mg/kg) would also far exceed upper continental crust values (Zn: 67; Cu: 25; Cr: 35 mg/kg), highlighting widespread multi-metal contamination. These enrichments would reflect combined anthropogenic inputs (agriculture, domestic discharges) and natural contributions. Unlike trace metals, iron and aluminum would display stable and homogeneous concentrations, confirming their lithogenic origin and role as tracers of the sedimentary matrix.

3.3. Spatial Distribution of Trace Metals

The distribution of trace metals (TMs) shows marked heterogeneity across sampling stations. Maximum concentrations of cadmium (52.19 mg/kg) and lead (1186.99 mg/kg) were recorded at ETUc-01 and ETUc-02, identifying these sites as critical hotspots of metal pollution. In contrast, ETUc-03 and ETUc-04 display lower concentrations, though still above geochemical background values. Nickel reaches an exceptionally high level at ETUc-03 (18.492 mg/kg), reflecting a predominantly lithological influence from the Birimian basement. At ETUc-04, Cd, Pb, and Hg concentrations are relatively reduced, confirming an uneven spatial distribution and suggesting a combination of natural and anthropogenic sources in the study area.

3.4. Vertical Variation of Heavy Metal Concentrations

Results indicate a differentiated vertical distribution of trace metals. The surface horizons (0 - 10 cm) exhibit the highest concentrations of cadmium (Cd), lead (Pb), nickel (Ni), and mercury (Hg). At ETUc-01, Cd reaches 52.19 mg/kg and Pb exceeds 1186.99 mg/kg. These extreme values point to pollution likely associated with human activities.

Intermediate horizons (10 - 20 cm) still show elevated concentrations, though slightly lower than those in the surface layers, suggesting progressive accumulation of heavy metals over time.

Deeper horizons (20 - 30 cm) present concentrations closer to geochemical background values (UCC). Cd falls below 15 mg/kg, while Pb approaches 10 - 20 mg/kg, values comparable to natural levels.

3.5. Geochemical Characterization of Contamination

The assessment of sediment contamination in Aby Lagoon through geochemical indices provides a comprehensive understanding of both the origin and intensity of trace metal pollution. The enrichment factor (EF) reveals extremely high values for cadmium (Cd), lead (Pb), and mercury (Hg), far exceeding the threshold of 10, which is generally considered indicative of strong anthropogenic influence. Cd reaches extreme values, ranging from 78.675 at ETUc-01 to 722.765 at ETUc-02, confirming massive and continuous inputs from artisanal gold mining and agricultural practices. Pb shows EF values between 215 at ETUc-04 and 8.855 at ETUc-

01, reflecting acute contamination attributable to urban effluents and industrial discharges. Hg also displays remarkable enrichment, with EF values ranging from 1.035 at ETUc-01 to 27.483 at ETUc-02, highlighting the direct impact of artisanal and small-scale gold mining (ASGM). Nickel (Ni) exhibits intermediate EF values (2.957 - 18.492), suggesting a dual origin: natural, linked to the weathering of the Precambrian Birimian basement rich in ferromagnesian minerals, and anthropogenic, through industrial and agricultural effluents. Other metals show more moderate enrichments: Zn ranges from 381 to 9652, Cu from 84 to 621, and Cr between 48 and 279. These values, generally below 5, indicate moderate inputs, mainly associated with diffuse agricultural and domestic discharges. Arsenic (As), however, presents high EF values (462 - 2303), confirming a significant anthropogenic contribution in addition to lithological influence associated with arsenopyrite in the Birimian basement.

The geoaccumulation index (Igeo) further supports these findings by highlighting contrasting levels of pollution across metals and sampling stations. As shown in **Table 5**, Cd values (6.38 - 7.55) correspond to class 6, indicating extremely polluted sediments and placing Aby Lagoon among the most affected areas in West Africa. Pb reaches an Igeo value of 4.39 at ETUc-01 (class 5: heavily to extremely polluted), but values at ETUc-02 (0.42) and ETUc-04 (-1.14) correspond to classes 1 and 0, respectively, revealing a heterogeneous spatial distribution. Ni shows Igeo values between 0.42 and 3.52, classifying sediments from moderately to heavily polluted, while Hg fluctuates between 0.53 and 2.56, confirming moderate to high contamination. In contrast, Cr and Cu show negative values, indicating an essentially lithogenic origin. As and Zn present low to moderate values, consistent with diffuse agricultural and mining inputs.

Table 5. Geoaccumulation index (Igeo) of trace metals across sediment cores.

Metal	ETUc-01	ETUc-2	ETUc-03	ETUc-04	Max Class
Arsenic (As)	0.13	-1.01	-0.64	0.10	1
Cadmium (Cd)	7.55	7.28	6.38	7.40	6
Chromium (Cr)	-3.13	-4.06	-4.39	-3.25	0
Copper (Cu)	-2.33	-2.90	-3.51	-2.49	0
Mercury (Hg)	1.30	2.56	0.53	1.93	3
Nickel (Ni)	2.81	0.42	2.72	3.52	4
Lead (Pb)	4.39	0.42	-1.33	-1.14	5
Zinc (Zn)	-0.15	1.05	-0.94	0.78	2

The Igeo results summarized in **Table 5** confirm extreme contamination by Cd and Pb, significant contamination by Hg and Ni, and moderate contamination by Zn and As, while Cr and Cu remain of lithogenic origin. These findings highlight the urgent need to assess the actual toxicological risk to aquatic biodiversity, particularly through the effect range quotient (ERQ).

Finally, the effect range quotient (Mean-ERQ) provides an ecological perspective by estimating the probability of biological effects. Stations ETUc-01 and ETUc-04 represent critical zones, with probabilities of biological effects exceeding 49%, while ETUc-02 and ETUc-03 show intermediate risks (21% - 49%). Overall, the presence of Cd, Pb, and Ni at critical levels constitutes a major threat to aquatic biodiversity. These results emphasize the urgent need for a thorough toxicological risk assessment and the implementation of appropriate environmental management measures to mitigate the impact of multi-metal contamination on Aby Lagoon's ecosystem.

4. Discussion

The measured concentrations of Cd, Pb, Ni, and Hg in Aby Lagoon exceed geochemical background values (Wedepohl, 1995) by several orders of magnitude. Such anomalies cannot be attributed solely to natural processes, as they indicate a major disruption of geochemical equilibrium. Unlike the observations of Togbé et al. (2023) in the Abidjan lagoon bays and Ebrié Lagoon, where enrichments remain significant but contained, Aby stands out for its intensity of contamination, systematically surpassing ecotoxicological thresholds.

Studies by Kouakou et al. (2024) in Digbougé Lagoon and M'Bra et al. (2026) in Grand-Lahou Lagoon reported moderate enrichments in Cd and Cr. Although concerning, these results reflect chronic but limited pollution. In contrast, Aby presents values that go beyond simple contamination, pointing instead to an environmental crisis. According to Sombo (2002), high Cd and Hg levels are directly linked to artisanal gold mining, where mercury is used for gold amalgamation. Pb and Zn likely originate from urban and industrial discharges, as well as agricultural inputs (Yao et al., 2009). Ni and Cr may be partly attributed to the weathering of the Precambrian basement (Bessoles, 1977). Together, these metals in Aby Lagoon reveal extreme multi-metallic pollution, reflecting a superposition of recent anthropogenic inputs.

This combination of natural and anthropogenic sources demonstrates that pollution is multifactorial, but with a clear dominance of current human activities. The spatial gradient (higher concentrations upstream, decreasing downstream) and vertical gradient (high concentrations in surface horizons, values closer to background at depth) confirm that contamination is chronologically recent. Unlike older deposits that reflect slow accumulation, Aby shows a sharp intensification of anthropogenic inputs over the past decades. This recent dynamic increases risk, as it indicates that pollution is active and ongoing.

Furthermore, calculated indices ($EF > 10$, $I_{geo} > 5$) classify sediments as heavily polluted, particularly for Cd and Hg. Sediment quality thresholds defined by MacDonald et al. (2000) are largely exceeded, implying a high ecotoxicological risk for benthic organisms. In addition, the bioaccumulation of Cd, Pb, and Hg within the trophic chain could affect lagoon biodiversity and pose a danger to human health (Kouamenan et al., 2020). Aby Lagoon therefore cannot be analyzed merely as an

extension of dynamics observed elsewhere; rather, it represents a unique case requiring differentiated management strategies.

5. Conclusion

The geochemical analysis of sediments from Aby Lagoon, particularly in the Etuessika-Assinie Canal sector, reveals severe multi-metal contamination. Concentrations of Cd, Pb, Ni, and Hg largely exceed upper continental crust background values, with geochemical (Igeo, EF) and ecotoxicological (Mean-ERQ) indices suggesting significant pollution. Cadmium and lead could be linked to agricultural and urban inputs, while the extreme mercury levels might reflect the influence of artisanal gold mining through gold-mercury amalgamation. Nickel, in turn, could result from both lithogenic sources and anthropogenic contributions, underscoring the complexity of contamination pathways.

Ecotoxicological assessment indicates probable biological effects (>49%) at three stations, mainly driven by Cd, Pb, and Ni, suggesting an overall alteration of the sector's biological integrity. These findings position Aby Lagoon as an ecosystem potentially threatened by metal pollution. They highlight the need for regular environmental monitoring, stricter regulation of anthropogenic activities, and complementary studies integrating chemical speciation, bioaccumulation, and temporal monitoring. Such an approach would be essential to refine the evaluation of ecotoxicological and health risks and to define management measures adapted to the sustainable preservation of this lagoon ecosystem.

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Author Contributions

All authors contributed to the conceptualization of the manuscript. The first author was responsible for the writing and preparation of the original draft, as well as its editing. The second and third authors contributed to the critical revision of the manuscript. Finally, all authors have read and approved the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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