An Innovative Toxic Heavy Metals Monitoring Product Development for a Sustainable Industry: A Case Study of Smartphone-Based Electrochemical Analytical Device

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Abstract

The understanding of Smartphone-Based Electrochemical Analytical Device (SEAD) development for monitoring heavy metal contaminants in wastewaters from industrial manufacturers contributes to environmental sustainability. The herewith-presented applied research of six case studies in Thailand is aimed to preliminarily scrutinize the industrial user's willingness to adopt the novel SEAD technology for monitoring a sustainable environment. This research employs the practical application of scientific methods and the concurrent triangulation strategy of integrating Quality Function Deployment (QFD) with a qualitative approach based on in-depth interviews. SEAD prototype was developed to test with lead and extreme users to assess their adoption determinants as well as the product's performance. The proposed SEAD was successfully applied to the determination of As(III), Cd(II), Pb(II) and Hg(II) in standard samples. A real wastewater sample from a battery manufacturer exemplified an effective detection of four metals. The results demonstrated rapid, economical, reproducible, and reliable analytical capabilities of SEAD, which will be useful for sustainable industrial wastewater screening. Analysis of data from industrial user interviews revealed that industrial buyer innovation adoption (IBIA) determinants, which are seller, buyer organization, individual user, technological innovation and external environments impact SEAD adoption. This research contributes to the understanding of SEAD's transition from scientific knowledge into sustainable technology and diffusible innovation.

Keyword: Smartphone-based electrochemical device/ Toxic heavy metals quantification/ Industrial buyer innovation adoption/ Environmental waters/ Industrial sustainability

1. Introduction

The World Health Organization (WHO) has called for an urgent need in managing ten chemicals of major public health concern, including four heavy metals, which are arsenic, cadmium, lead and mercury (WHO, 2010). With the global concerns on toxic heavy metals screening and management, electrochemical analytical paper-based devices (ePADs) have gained significant attention among researchers during the past decade for their capabilities in environmental monitoring (Atide et al., 2020). The smartphone-based electrochemical analytical devices (SEAD) are developed from the integration of ePADs and smartphone communicating technologies, simplifying sophisticated electrochemical experiments on handheld devices. The potentiometric methods using selective electrodes on ePADs can quantify toxic heavy metals instantly, accurately and portably with the aid of wireless technologies (e.g., Bluetooth, Near-Field Communication (NFC), Wi-Fi) on smartphones (Steinberg et al., 2015, Krorakai, 2021). However, SEADs are still struggling from transforming R&D research into comercializable and sustainable innovation.

By understanding the insights of stakeholders, we will be able to develop new

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product strategies for assessing the risk of toxic chemicals in the environment. The challenges of new product development are not only user's satisfaction in innovative quality, but are also strict industrial standards and environmental legislations. SEAD innovation is targeted to support sustainable digital transitions of our economy and society for monitoring contaminated water, which is aligned with the European Commission's Chemicals Strategy for Sustainability Towards a Toxic-Free Environment (2020). The ultimate goal of SEAD is not about saving money or time, but it is about saving lives in global communities as well as supporting four UN Sustainable Development Goals (UN SDG), which are (1) clean water and sanitation, (2) industry, innovation and infrastructure, (3) life on land and (4) life below water.

1.1 SEADs and smartphone communicating technologies

The concept of SEAD is developed from ePADs with the integration of smartphone communicating technologies. The electrochemical analytical methods are suitable for environmental monitoring due to their selectivity, reproducibility, speed, and reliable analytical capability (Ataide et al., 2020, Shamkhalichenar et al., 2020). ePADs quantify heavy metal ions by redox reactions, which selectively measure the electron transfer in the microvolume of an electrochemical cell with voltammetric techniques between modified electrodes (i.e., reference electrode, working electrode and auxiliary electrode) (Aragay et al., 2011, Skoog et al., 2017). Previously developed ePADs' limits of detection were compliant with the international guidelines in Table 1. For instance, Kim and Kim (2017) demonstrated ePAD determining 0.1 µg L^{-1} of As(III). Chaiyo et al., (2016) developed ePAD to detect 0.1 µg L^{-1} of Cd(II) and Pb(II). Sánchez-Calvo et al., (2019) introduced ePAD measuring 0.0012 µg L^{-1} of Hg(II). Although these ePADs were miniaturized, they were still required to work with bulky workstations and potentiostats.

Table 1. Water quality guidelines for heavy metals (µg L^{-1} or ppb) (Lace & Cleary, 2021, Industrial Effluent Standards, 2017)

Heavy Metal	Drinking water				Wastewaters
	Oxidation States	WHO	European Union	US Environmental Protection Agency (US EPA)	Department of Industrial Works (DIW, Thailand)
Arsenic (As)	III, V	10	10	10	250
Cadmium (Cd)	II	3	5	5	30
Lead (Pb)	II	10	10	15	200
Mercury (Hg)	I, II	1	1	2	5

Smartphone wireless communication technologies can be integrated with SEADs as an application of portable electrochemical impedance spectroscopy (EIS). Electrochemical analysis requires modified electrodes, which are connected to an electronic instrument (i.e., potentiostat or galvanostat) to control the voltage difference between a working electrode and a reference electrode. The experiments of former EIS systems were difficult as they relied on wired computers. Nevertheless, wireless communication technologies available in smartphones can replace wired computers and connections with Wi-Fi, Bluetooth or NFC. To illustrate, Steinberg et al. (2015) has previously demonstrated the proof of concept of a credit card-sized wireless NFC potentiostat with an electrochemical sensor to measure blood glucose with smartphones. Each wireless technology has advantages and disadvantages as shown in Table 2. Distinctly, the most suitable technology for SEADs is NFC as it can draw power from a smartphone's battery, making the devices portable, wireless and powerless.

Table 2. Comparison of smartphone wireless technologies (Khorov et al., 2018, Woolley & Schmidt, 2017, NFC Technology, n.d.)

Wireless technology	Wi-Fi 802.11ax	Bluetooth 5.0	NFC
Signals	Ultra-High Frequency (UHF), Super High Frequency (SHF), Industrial, Scientific and Medical band (ISM)	UHF, ISM	Radio Frequency Identification (RFID)
Frequency range	1-6 GHz	2.402-2.480 GHz	13.56 MHz
Propagation distance	>100 meters	40-500 meters	<10 centimeter
speed	10 Mbit/s	2 Mbit/s	424 Mbit/s
Power source	Required active batteries	Required active batteries	Operated from passive electromagnetic induction

1.2 Quality Function Deployment (QFD)

QFD is a systematic technique that helps organizations to design, improve and develop new products based on the identification of customers' needs, which are linked and aligned with the organizational processes, functions and goals (Akao, 1997). The method has also been applied widely in various industries to develop sustainable technologies. For instance, Vinodh & Chintha (2011) provided evidence of the QFD approach for ensuring a sustainable manufacturing practice. QFD successfully improved volatile organic compounds abatement in aluminium foil surface coating (Gupta & Modi, 2018). The user's needs and perception in substituting petrochemical plastic for bioplastic adoption were scrutinized by QFD (bin Ahmad Shamsuddin et al., 2015). Moreover, other strategic quality management tools (e.g. TRIZ, AHP, Value Engineering, SERVQUAL) were also combined with QFD to create innovative products in various industries such as automobiles, healthcare, electronics, software, and utilities (Thawesaengskulthai, 2019).

QFD matrix or the House of Quality (HOQ) shows the relationship between the customer's requirements and the product's attributes, which will be useful to enhance new product development, especially the SEAD technology as the framework is a structured customer-focused approach.

1.3 Sustainable industrial dynamics

Features of sustainability rely on interconnected three pillars, which are environmental, economic and social (Barbier, 1987). Technological development has also been considered a sub-domain of sustainable development (Magee et al., 2013) as science, technology and innovation improve economic growth and social well-being (Schumpeter & Opie, 1934, OECD, 2000). However, developed technology capabilities and trajectories could potentially exceed users' needs, exploiting resources and time. The economic and institutional factors play a pivotal role in selecting radical and incremental innovators, who will survive in the competitive environment by taking risks in trial-and-error processes (Dosi, 1982). To minimize business failures, Rothwell (1994) proposed an innovation coupling model, which suggests sellers understand the market's needs, and also internally and externally communicate and assess their technological innovation. The coupling strategy between seller and buyer can be viewed as an integration of Technology Acceptance Models (TAM) and consumer behavior theories. The seller's and buyer's objectives should be aligned to develop and implement sustainable new products in the industry. From buyers' perspectives, TAMs analyze users' intention to use from attitudes that are influenced by external variables, perceived usefulness and perceived ease of use (Davis, 1989). Similarly, Kotler (1997) suggested that the buying process starts from communication with the target audience through various channels, which results in a purchasing decision. The process involves the environment, the organization, sellers, and individual participants who play different roles as users, influencers, decision-makers, buyers and gatekeepers (Webster and Wind, 1972). As this study focuses on identifying user's determinants with the adoption of the novel SEAD technology for monitoring sustainable environment, we propose that there are five factors (seller, buyer organization, individual user, technological innovation and external environments) that impact SEAD adoption for the sustainable heavy metal-free environment as summarized in Table 3.

Table 3. Determinants influencing SEAD adoption for sustainable heavy metal-free environment (Adapted from Thanabodypath et al. (2021)

Determinants	Description
1. Seller	A new solution or technology offered by sellers is a key to improving sustainability by aligning their strategies to support users' targets and UN SDGs. The seller stimulus interactions help users to identify their needs effectively through communication channels and influencers, which will result in an adoption intention.
2. Buyer organization	Sustainable sourcing practices ensure supply chain operations. Buyers enhance their sustainability with suppliers by assessments and certifications. A network of trusting relationships will assist a decision on new technology adoption based on a mutual goal and a shared appreciation of innovation development.
3. Individual user	Organizations require internal people to assess new solutions. Perceived usefulness, perceived ease of use and internal people characteristics impact users' attitudes, intentions and behaviors. Individual-level and group-level actions impact an organization's dynamic capabilities from adopting environmentally sustainable innovation.
4. Technological innovation	Relative advantage, complexity, and compatibility lead to adoption in the innovation-decision process. Perceived superior technological advantages with less spent resources will make users more likely to adopt new technology. Additional attributes (e.g., standards, cost, and accuracy) of new technology are taken to benchmark against existing rivals. If a new technology is more advantageous and sustainable, users will be more likely to adopt it.
5. External environments	Environmentally beneficial technologies in the chemical-related industries are more likely to diffuse earlier than technologies that are contrary to directions of external environment trends. Sustainable challenges imposed by external environments impact users' adoption decisions, especially in aspects of regulations, economics, society, culture and technological infrastructure.

In brief, SEAD technology capabilities should be scrutinized holistically from users' and researchers' perspectives to address industrial adoption barriers for monitoring a sustainable environment. QFD and determinants influencing SEAD adoption will be assessed by instruments and methods in the next section.

2. Methodology

2.1 SEAD materials and methods

Although the electrochemical technologies and wireless potentiostats are available for research and development, a commercial product using such techniques for industrial heavy metals monitoring in the environment is still absent on the market. They were made and intended to be experimented in laboratories by skilled technicians only. Our newly developed SEAD concept for industrial users comprises of four components, which are (1) nanomaterials modified screen-printed graphene electrodes (SPGEs) or sensors, (2) supporting electrolyte, (3) customized NFC potentiostat, and (4) NFC enabled Andriod smartphone. The system is designed to detect arsenic(III), cadmium(II), lead(II) and mercury(II), which are chemicals of major public health concern specified by WHO (2010).

Standards for four metal assays were prepared from sodium arsenite, cadmium(II), lead(II) and mercury(II) standard solution for AAS (Sigma-Aldrich, Missouri, USA). Potential interferences were prepared from iron(III) chloride hexahydrate, nickel(II) sulfate hexahydrate, potassium dichromate, magnesium chloride, iron(II) sulfate, sodium chloride, potassium chloride, calcium chloride, aluminium, chromium(VI), zinc(II) and copper(II) standard solution for AAS (Merck, Darmstadt, Germany). Silver/silver chloride ink was purchased from the Gwent group (Gwent Electronic Materials, UK). Carbon ink was purchased from Acheson (California, USA). Bismuth(III) for AAS was purchased from Sigma-Aldrich (Missouri, USA). Copper phthalocyanine was purchased from Sigma-Aldrich (Missouri, USA). All solutions were prepared with deionized water (18.2 MΩ.cm) from a Milli-Q system (Millipore, UK). A stock solution of arsenic(III), and mercury(II) were prepared by dissolving in 0.1 mol L^{-1} HCl, and stock solution of cadmium(II), lead(II) were dissolved in 0.2 mol L^{-1}.

The screen-printed electrodes were fabricated on a polyvinyl chloride sheet to make sensors for electrochemical detection using techniques from our previously published methods with a modification as summarized in Table 4. Additionally, the shelf life of sensors was tested by a laminated film and stored in a re-sealable zipper storage plastic with silica gel.

Table 4. Modification of screen-printed graphene electrodes (SPGEs) or sensors used in SEAD for sustainable heavy metal-free environment

Referenced methods	Proposed modified electrodes and supporting electrolytes in this work			
Analyte	Working electrode	Reference electrode	Counter electrode	Supporting electrolyte
As(III) (Pungjunun et al., 2018)	SPGE	Screen-printed Ag/AgCl	SPGE	HCl + Au(III)
Cd(II) and Pb(II) (Chaiyo et al., 2016)	Bi(III) in-situ/SPGE	Screen-printed Ag/AgCl	SPGE	HCl
Hg(II) (Chaiyo et al., 2014)	Copper phthalocyanine (CuPc)/SPGE	Screen-printed Ag/AgCl	SPGE	HCl

The differential pulse voltammetric electrochemical measurements were performed by using a customized credit-card sized NFC potentiostat with SIC4341 microchip (Silicon Craft Technology PLC, Bangkok, Thailand), which acquired energy from the electromagnetic induction emitted from Motorola One Smartphone (Motorola, IL, USA). iQuan Andriod mobile application was newly developed to control the NFC potentiostat for this SEAD system.

The quantification of SEAD hinges on three steps (Figure 1). The first step is sample preparation. A standard sample of each heavy metal is mixed with a supporting electrolyte at a specified ratio. The second step is sensor calibration by connecting a specified heavy metal sensor with NFC potentiostat, which is controlled by iQuan application. Then, an Andriod smartphone is tagged over the NFC potentiostat. Thirdly, the application will ask a user to drop the mixed solution on a sensor covering all electrodes. The mobile device will automatically quantify and display the test result.

2.2 Participants

Purposive sampling was used as the basis of interviewees selection. Lead and extreme users from 40 industrial corporations in Thailand that regularly monitored heavy metal contaminants in water were offered to test the SEAD prototype in person at their factories. Potential participants were approached by telephone calls to explain the study objectives and methods. After that the official letters were sent to them by email and post. Six industrial leaders volunteered to test provided SEAD system with standard samples and participate in the interview. The interviewees were managers and experts, who were familiar with the environmental heavy metal analysis. Their internal test methods included colorimetry, atomic absorption spectrometry (AAS), inductively coupled plasma mass spectrometry (ICP-MS) and portable photometers (Table 5).

To understand SEAD adoption drivers, data sources were triangulated through the convergence of interviewees' qualitative information as explained in section 3.3. QFD was also used to quantitatively synergize SEAD users' needs and the product's technical features.

Step 1. Sample preparation
Step 2. Sensor calibration
Step 3. Heavy metal quantification

Figure 1. The system of SEADs for environmental toxic heavy metal quantification with an NFC-enabled smartphone.

Table 5. Interviewees profile

Code	Job role	Industry	Internal Heavy metal test method	Test frequency
No.1	Factory manager	Semiconductor	Colorimetry	1 time/weekly
No.2	Factory manager	Waste treatment	ICP-MS	1 time/daily
No.3	Environmental manager	Industrial estate developer	Colorimetry	1 time/daily
No.4	Technical expert	Chemical manufacturer	ICP-MS	1 time/daily
No.5	Technical expert	Water treatment	AAS	1 time/daily
No.6	Technical expert	Batteries manufacturer	Colorimetry, portable Bluetooth photometer	3 times/daily

2.3 Technology acceptance determinants

The data were collected from face-to-face semi-structured interviews at participant's organizations. The duration of the interview was between 40 and 80 minutes. Interview questions were designed to assess five adoption determinants of SEAD technology for a sustainable heavy metal-free environment, which are sellers, buyer's organizations, individual users, technological innovations and external environments. Probing questions in each determinant were used to obtain detailed insights from real users. Since this is an exploratory research, the researchers aimed to examine how these five determinants and their sub-factors influence sustainable technology adoption. The content analysis was used to construct a novel industrial buyer innovation adoption model (IBIA) from the literature review and the collected emerging primary data.

2.4 QFD

QFD processes quantify and benchmark the user's requirements against the developer's targeted technical specifications as shown in Figure 2 and Table 6. The QFD tool can be early applied in the product life cycle and be reiterated in four phases from product planning (engineering characteristics), product designing (part characteristics), process planning (process parameters) and process controlling (production operations) (Moubachir & Bouami, 2015). The QFD assessment played a significant role in this study as the researcher aimed to bring the new SEAD for heavy metals quantification to the market for the first time. Innovations failed from technology-push approaches. Thus, the development of new technological products also heavily relies on customers' needs. The QFD process was completed in a single iteration of the product planning stage. The assessment criteria in the QFD matrix were agreed and made by the SEAD developer team based on primary and secondary data. To explore industrial users' hesitation with the adoption of the novel SEAD technology for monitoring sustainable environment, interviewers were asked a series of questions to scrutinize their needs and ratings on SEAD attributes.

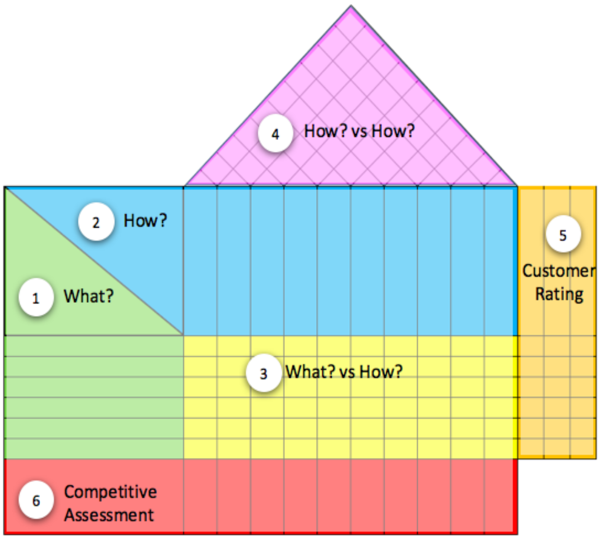

Figure 2. QFD Matrix or the House of Quality (HOQ)

Table 6. QFD Processes and Actions Adapted from Dehe & Bamford (2017)

QFD Processes	Actions
1. What?	Defining customer's requirements or the voice of customers (VOC) with a weight of importance
2. How?	Establishing product's technical features or the voice of business (VOB)
3. What? vs How?	Analyzing relationships between VOC and VOB
4. How? vs How?	Analyzing correlations and trade-offs between each technical feature
5. Customer Rating	Comparing the new product's quality with competitors' by customers
6. Competitive Assessment	Benchmarking the new product's quality with competitors' within an organization based on technical targets and objectives

3. Results and Discussion

3.1 SEAD performance

The analytical performance of SEAD under the optimized condition is summarized in Table 7. The differential pulse voltammetry (DPV) was chosen to develop with the NFC potentiostat as this electrochemical method was simple with a distinct peak current compared to the linear scan and square-wave methods (Nigović & Šimunić, 2003). The limits of detection (LOD) were 7.54 µg L^{-1}, 3.95 µg L^{-1}, 1.90 µg L^{-}1 and 32.80 µg L^{-1} for As(III), Cd(II), Pb(II) and Hg(II), respectively. Our SEAD's LODs (except mercury) were compatible with EU, US EPA and DIW standards in Table 1. Ten sensors and ten NFC potentiostats were prepared under the same conditions. The relative standard deviations were ≤10%, respectively, indicating high sensor-to-sensor reproducibility.

To verify the precision and accuracy, results obtained from our method were compared with the inductively coupled plasma atomic emission spectroscopy (ICP-OES) method by using a battery manufacturer's real wastewater samples. The experiments were performed and evaluated using samples spiked with three levels as shown in Table 8. No As(III), Cd(II), and Hg(II) were found in the real samples. The %RSD and %recoveries values were in the ranges of 0.1-6.5% and 83.40-109.4% for the proposed method, respectively. These results showed good agreement with the results obtained from the ICP-OES method. Paired samples t-tests were used to compare means of results from both methods. The calculated p-values were below 0.05 threshold, confirming that there was no significant difference between the two methods.

Table 7. SEAD analytical performance

Analyte	Linear range (µg L^{-1}, ppb)	Regression	LOD (µg L^{-1}, ppb)	RSD (%)	Deposition potential (v)	Deposition time (s)
As(III)	20-1,000	$y = 0.0374x + 1.5564$ ($R^2 = 0.9936$)	7.54	6.2-8.8	-0.5	160
Cd(II)	50 – 1,500	$y = 0.0566x - 1.4592$ ($R^2 = 0.9971$)	3.95	3.8-10.4	-1.1	180
Pb(II)	50 – 1,500	$y = 0.0436x - 1.1305$ ($R^2 = 0.9908$)	1.90	2.2-3.8	-1.1	180
Hg(II)	100-3,000	$y = 5.1604x + 0.5767$ ($R^2 = 0.9977$)	32.80	3.0-5.2	-0.8	60

Table 8. The comparison of SEAD and ICP-OES results

As(III)							
Samples		Proposed method			ICP-OES		
	Spiked (µg L^{-1})	Found			Found		
		$\bar{X}$±SD (µg L^{-1})	%RSD	%recovery	$\bar{X}$±SD (µg L^{-1})	%RSD	%recovery
Pre-treatment	non-spike	ND	-	-	ND	-	-
	200.0	166.9±9.1	5.5	83.4	168.7±2.6	1.5	84.3
	400.0	374.4±24.3	6.5	93.6	389.4±1.7	0.4	97.4
Post-treatment	non-spike	ND	-	-	ND	-	-
	200.0	172.0±8.8	5.1	86.0	170.8±3.3	1.9	85.4
	400.0	379.0±20.1	5.3	94.8	383.8±3.2	0.8	95.9

Cd(II)							
Samples		Proposed method			ICP-OES		
	Spiked (µg L^{-1})	Found			Found		
		$\bar{X}$±SD (µg L^{-1})	%RSD	%recovery	$\bar{X}$±SD (µg L^{-1})	%RSD	%recovery
Pre-treatment	non-spike	ND	-	-	ND	-	-
	300.0	265.2±8.6	3.2	88.4	279.2±0.5	0.2	93.1
	500.0	430.9±21.6	5.0	86.2	485.1±0.6	0.1	97.0
Post-treatment	non-spike	ND	-	-	ND	-	-
	300.0	320.4±2.7	0.9	106.8	260.3±0.9	0.3	86.8
	500.0	474.8±0.4	0.1	95.0	442.9±0.9	0.1	88.6

Pb(II)							
Samples		Proposed method			ICP-OES		
	Spiked (µg L^{-1})	Found			Found		
		$\bar{X}$±SD (µg L^{-1})	%RSD	%recovery	$\bar{X}$±SD (µg L^{-1})	%RSD	%recovery
Pre-treatment	non-spike	3437.7±106.1	3.1	-	3,530.4±0.8	0.02	-
	300.0	3739.3±154.4	4.1	100.5	3,840.1±3.3	0.09	103.3
	500.0	3878.3±137.4	3.5	88.1	4,030.0±5.9	0.15	99.93
Post-treatment	non-spike	80.1±1.1	1.3	-	79.8±1.7	2.2	-
	300.0	387.6±10.4	2.7	109.4	343.2±2.9	0.9	87.8
	500.0	580.1±27.9	4.8	99.9	594.0±5.1	0.9	102.9

Table 8. The comparison of SEAD and ICP-OES results (cont.)

Hg(II)							
Samples		Proposed method			ICP-OES		
	Spiked (μg L^{-1})	Found			Found		
		$\overline{X}$±SD (μg L^{-1})	%RSD	%recovery	$\overline{X}$±SD (μg L^{-1})	%RSD	%recovery
Pre-treatment	non-spike	ND	-	-	ND	-	-
	500.0	510.9±14.1	2.8	102.2	505.9±0.3	0.1	101.2
	1,000.0	891.5±43.2	4.9	89.2	1,026±0.0	0.0	102.6
Post-treatment	non-spike	ND	-	-	ND	-	-
	500.0	498.1±19.2	3.9	99.6	492.5±1.9	0.4	98.5
	1,000.0	934.5±9.4	1.0	93.4	952.7±1.4	0.1	95.3

ND: Not detected

The interference study was performed by adding metal ions that were also found in environmental waters and wastewaters into a standard solution. The tolerance ratio of interference for a signal change for 0.5 µg mL^{-1} As(III), 1 µg mL^{-1} Cd(II), 1 µg mL^{-1} Pb(II) and 1 mg mL^{-1} Hg(II) are listed in Table 9. The results illustrated SEAD offered outstanding selectivity in the detection of As(III), Cd(II), Pb(II) and Hg(II) with the percent deviation of all interfering environmental metals were less than ±5.0%. However, a presence of Cu(II) in samples competed against signals and peaks of As(III), Cd(II), Pb(II) and Hg(II). Therefore, Cu(II) should be eliminated to improve SEAD for environmental heavy metal detection capabilities. To improve the peak signal and reduce the interference of Cu(II), ferricyanide will be added in electrode fabrication in future development.

The screen-printed electrodes were stored in four different environments, including Ziplock bag, plastic wrap and silica gel as displayed in Figure 3. The shelf life of sensors in all environments still performed similar results with only ±5% deviation after 60 days from the manufactured date.

Table 9. SEAD environmental metals interference

		Interference and tolerance ratio							
		Ca(II)	Mg(II)	K(I)	Fe(II)	Zn(II)	Na(I)	Cd(II)	Ni(II)
Analyte	As(III)	1,000	1,000	1,000	1,000	1,000	1,000	500	500
	Cd(II)	250	500	500	2.5	25	500		25
	Pb(II)	1,000	1,000	1,000	500	50	1,000		500
	Hg(II)	1,000	1,000	1,000	100	10	1,000	500	10

		Interference and tolerance ratio						
		Al(III)	Fe(III)	Cr(VI)	Pb(II)	Hg(II)	As(III)	Cu(II)
Analyte	As(III)	500	100	10	10	10		1
	Cd(II)	25	25	2.5		1	1	0
	Pb(II)	50	500	2.5		10	1,000	0
	Hg(II)	500	10	10	100		0	0

3.2 QFD result

QFD was used to assess the industrial users' key elements in adopting SEAD for toxic heavy metal quantification. SEAD was intended to be tested with environmental and industrial wastewaters, but many water sources were highly contaminated with Cu(II), which interfered SEAD system. As a result, the SEAD prototype was tested with standard samples by six lead and extreme users in their actual work environment. A six-step QFD process from Table 6 was used to analyze SEAD attributes.

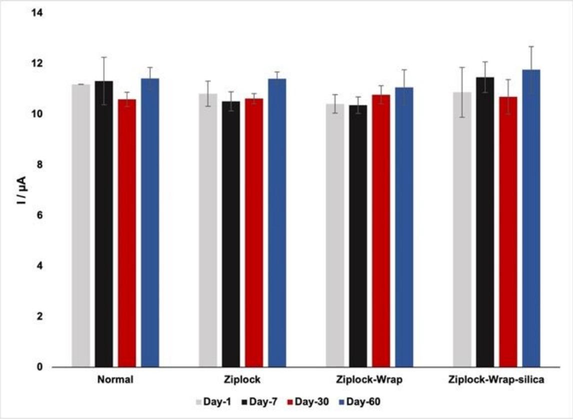

Figure 3. Sensors shelf life in different storage environments

Firstly, interviewees were asked to rate the importance of 10 user's demanded qualities in usage, cost and standard perspectives. A five-point rating scale was used for all measurement items (1=extremely unimportant, 2=unimportant, 3=neutral, 4=very important, 5=extremely important). The weight/importance scores in Figure 4 were averaged scores from 6 interviewees. 'Ease of use in organization and environment', 'fast and instant test results', 'reducing test expenses' and 'device accuracy' were the most demanded SEAD attributes. 'Low equipment maintenance', 'cleaning time and procedure after use', 'portability' and 'environmental-friendly equipment and methods' were very important while 'smartphone integration' attribute received the lowest score (3.8), yet still above neutral.

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Secondly, decision-makers established a set of 10 product characteristics. These technical features allowed SEAD developers to define the measurable functional and operational requirements of the system.

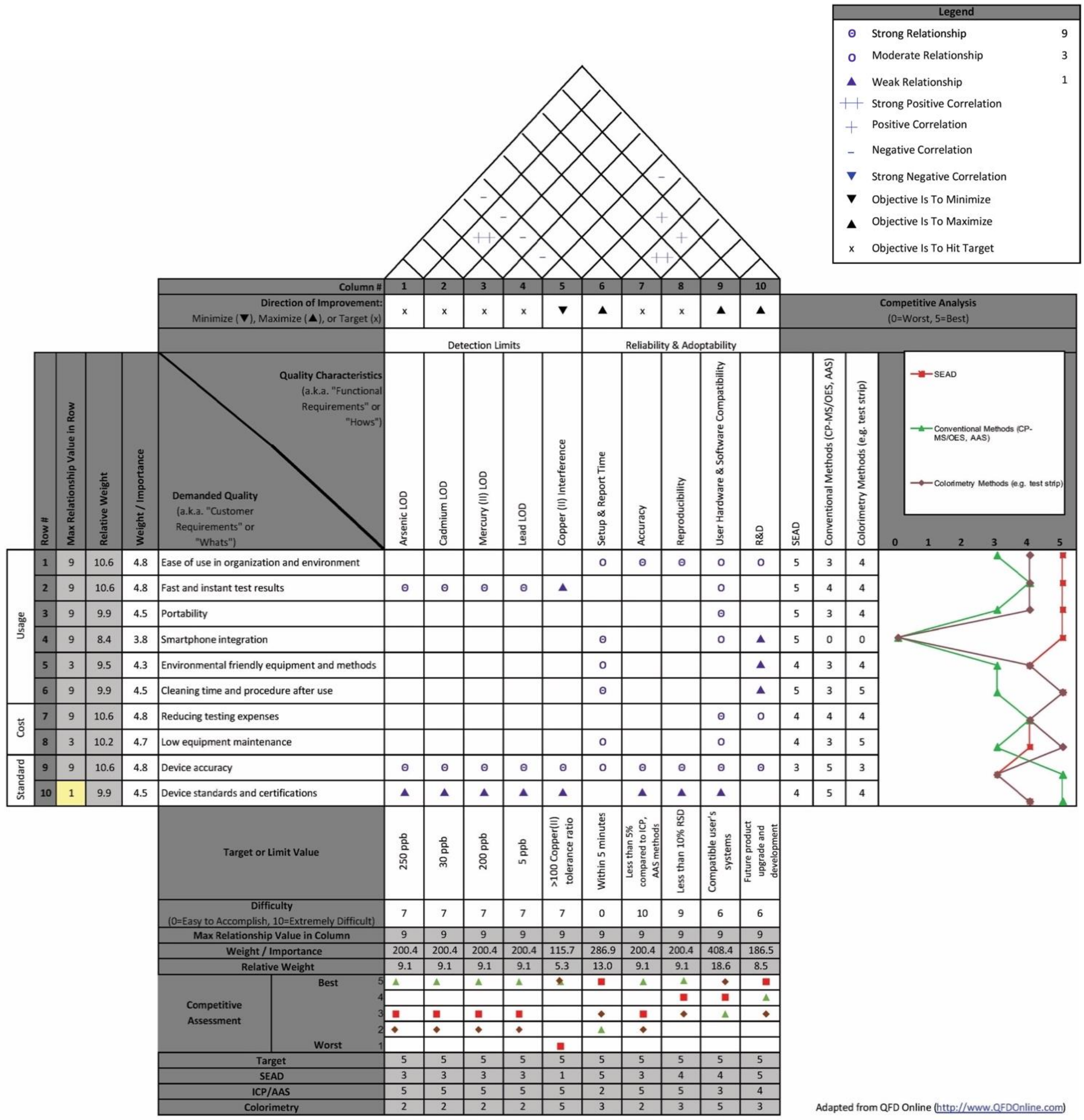
Thirdly, the relationships between the user's demanded qualities and the developer's technical requirements were agreed by decision-makers in 3 intensities (1 or ▲=weak relationship; 3 or O=moderate relationship; 9 or Ɵ=strong relationship). Although ePAD and SEAD technologies were widely adopted in research laboratories, they are still new to the industry with no certified international standard. Hence, 'device standards and certifications' had weak relation to almost all quality characteristics. The decision-makers deemed that 'setup and report time', 'user hardware and software compatibility' and future 'R&D' would moderately increase user's attention as these attributes enhanced usability in internal and external environments. Users would be able to acquire accurate heavy metal monitoring results with low maintenance costs by utilizing environmentally responsible testing equipment and methods. Compatible limits of detections for As(III), Cd(II), Pb(II) and Hg(II) with international regulations encouraged users to shift to new technology. A smartphone integration with four-metal-analysis in one device also helped users to reduce testing expenses. Therefore, the detection limit qualities were agreed to have strong relationships with 'fast and instant test results' and 'device accuracy' attributes.

Fourthly, the decision-makers analyzed correlations and trade-offs between each technical feature. 'Cadmium LOD' and 'lead LOD' had a positive strong correlation since the developed sensor could simultaneously detect both metals. 'Accuracy' and 'reproducibility' were also strongly correlated as SEAD results should be able to be repeated and compared with conventional test methods. The 'user hardware and software compatibility' had a positive correlation with 'setup and report time' and 'accuracy'. SEAD system should be hassle-free for users in syncing NFC potentiostats with sensors and smartphones to monitor environmental contaminants timely and accurately. However, negative correlations between four metals and interfering Cu(II) should be minimized in future research and development.

Fifthly, QFD compared SEAD capabilities against market competitors, specifically colorimetric (e.g., test strips) and conventional methods (e.g., ICP-MS, AAS) by allocating a score ranging between 0 (worst) and 5 (best).

From the user's perspective, SEAD was exceptional in its ease of use, instant test report and portability with smartphone integration. However, its accuracy and certification method should be improved to meet targeted international and industrial standards in the final step.

Finally, SEAD attributes were benchmarked the new product's quality with competitors' within an organization based on technical targets and objectives as seen in the bottom section of Figure 4. The priority was to eliminate Cu(II) interference in the system and improve all four metals detection limits to meet the industrial effluent standards of the Department of Industrial Works in Thailand. Clearly, accuracy, reproducibility and future product upgrade and development were also crucial for SEAD improvement in order to be adopted and replace conventional technologies.



	Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Arsenic LOD	Cadmium LOD	Mercury (II) LOD	Lead LOD	Copper (II) Interference	Setup & Report Time	Accuracy	Reproducibility	User Hardware & Software Compatibility	R&D	SEAD	Conventional Methods (CP-MS/OES, AAS)	Colorimetry Methods (e.g. test strip)
					Column #	1	2	3	4	5	6	7	8	9	10	Competitive Analysis (0=Worst, 5=Best)		
					Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	x	x	x	x	▼	▲	x	x	▲	▲			
						Detection Limits					Reliability & Adoptability							
Usage	1	9	10.6	4.8	Ease of use in organization and environment						O	Θ	Θ	O	O	5	3	4
	2	9	10.6	4.8	Fast and instant test results	Θ	Θ	Θ	Θ	▲				O		5	4	4
	3	9	9.9	4.5	Portability									Θ		5	3	4
	4	9	8.4	3.8	Smartphone integration						Θ			O	▲	5	0	0
	5	3	9.5	4.3	Environmental friendly equipment and methods						O				▲	4	3	4
	6	9	9.9	4.5	Cleaning time and procedure after use						Θ				▲	5	3	5
Cost	7	9	10.6	4.8	Reducing testing expenses									Θ	O	4	4	4
	8	3	10.2	4.7	Low equipment maintenance						O			O		4	3	5
Standard	9	9	10.6	4.8	Device accuracy	Θ	Θ	Θ	Θ	Θ	O	Θ	Θ	Θ	Θ	3	5	3
	10	1	9.9	4.5	Device standards and certifications	▲	▲	▲	▲	▲		▲	▲	▲		4	5	4

		1	2	3	4	5	6	7	8	9	10
Target or Limit Value		250 ppb	30 ppb	200 ppb	5 ppb	>100 Copper(II) tolerance ratio	Within 5 minutes	Less than 5% compared to ICP, AAS methods	Less than 10% RSD	Compatible user's systems	Future product upgrade and development
Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)		7	7	7	7	7	0	10	9	6	6
Max Relationship Value in Column		9	9	9	9	9	9	9	9	9	9
Weight / Importance		200.4	200.4	200.4	200.4	115.7	286.9	200.4	200.4	408.4	186.5
Relative Weight		9.1	9.1	9.1	9.1	5.3	13.0	9.1	9.1	18.6	8.5
Competitive Assessment	Best 5	▲	▲	▲	▲	◆ ▲	■	▲	▲	◆	■
	4								■	■	▲
	3	■	■	■	■		◆	■	◆	▲	◆
	2	◆	◆	◆	◆		▲	◆			
	Worst 1					■					
Target		5	5	5	5	5	5	5	5	5	5
SEAD		3	3	3	3	1	5	3	4	4	5
ICP/AAS		5	5	5	5	5	2	5	5	3	4
Colorimetry		2	2	2	2	5	3	2	3	5	3

Adapted from QFD Online (http://www.QFDOnline.com)

Figure 4. QFD of SEAD for Sustainable Heavy Metal-Free Environment

3.3 SEAD innovation adoption determinants

The interview data were analyzed based on content analysis from the transcripts. Keywords relating to SEAD innovation adoption determinants were identified, which are seller, buyer organization, individual user, technological innovation and external environments. Six interviewees admitted that all industrial buyer innovation adoption (IBIA) factors played an essential role in the innovation-decision process for monitoring heavy metal-free environments.

Sellers' actions influenced users' needs, reflected their directions in supporting users' sustainable targets, and supported their adoption intention. For example, interviewee No. 1 asserted that "*information exchange is vital as this would help users to proactively solve existing and potential problems. The seller should enhance the product lifecycle and shelf life of heavy-metal monitoring techniques. They should be environmentally disposable and storable. Some products that we purchased expired within 7 months, and these are financial and environmental wastes that we had to throw them away.*" Correspondingly, interviewee No. 3 experienced the same shelf life problem, stating that "*the reliable colorimetric test strips were difficult to find in the market and it took months to import from overseas. Colorimetric devices that we stored in our lab did not react in any color changes when we were assessing environmental waters. We could not get an assured result and also had to throw them away while the seller did not show any responsibility. We need to have a shared goal. Innovative technologies should provide multiple benefits to users, communities and the environment.*"

In the aspect of buyers and their internal organization, sustainable sourcing practices ensure the supply chain operations as well as enhance supplier's performances through assessments, certifications and networking. Interviewee No. 6 exemplified that *"the commitment in responsible procurement in a joint platform or a collaboration with suppliers promotes a decision on new technology adoption based on a shared appreciation of innovation development. The Headquarters establishes a single organizational standard that applies to all of branches in every country in order to fulfill customer's requirements with minimized risks from intra- and inter-organizational feedbacks."* Furthermore, *"if the new product can be customized for our uses in quantifying zinc oxide, we will be more likely to consider purchasing it. We seek resources integrity. The values of a heavy metal detection device are not only from its practical usability, but also from a sustainable return on investment."* – Interviewee No. 4

Individual users impact the organization's resources and capabilities by adopting environmentally sustainable innovation. Interviewee No. 1 affirmed that *"internal people characteristics impact personal's intention and behaviors in using any technology. Although our current heavy metal monitoring by a colorimetric method is very easy, sometimes the responsible employee neglected using the purchased devices in their routine inspections. Conversely, they used their own experience in estimating light blueish green colors of copper contaminants in wastewaters with bare eyes. We need to encourage our staff to collaborate with us. So, the new heavy metal detection technology should make users feel at ease. What we are concerned about SEAD is how the frontline users would take care of a smartphone and the NFC potentiostat. If the system is waterproof and could be immersed in water, that might be a good option."* In contrast, Interviewee No.3 was against colorimetric methods. *"Inspectors were afraid to make a judgment from unclear color variants when comparing the result with the device's color chart. Results can be biased from people's eyes and lights. Users have to take risks when reporting from color ranges, and sometimes we are not quite positive about the device's accuracy."*

SEAD technological innovations help users to reduce leakages and exposure to contaminants of toxic heavy metals in wastewaters. Relative advantage, simplicity, and compatibility lead to adoption in the innovation-decision process. According to Interviewee No. 5, *"we would switch to an alternative product, if a new heavy metal quantification device had a better technological quality, a competitive price and a certified standard. SEAD is great for rapid screening results, but it would be costly to find compatible smartphones, if it only operates with Andriod systems and specific potentiostats. For the electrochemical sensors, if each sensor could be reused 10 times, this would make us save more costs. Another thing to point out is* *the device calibration and standard. Apart from accurateness, we perceive that innovations, which are in compliance with international standards would help us maintain and attain a better industrial ecosystem. New technology should be calibrated to meet American Water Works Association (AWWA) or US EPA standards."* After testing the SEAD prototype, 5 of 6 interviewees showed their intention to purchase the device when it is completely developed. Its detection limit, reliability, reproducibility still need improvements to meet the targeted standard as advised by experts and guided by QFD assessment.

External environments place immense pressure to improve sustainability practices. All interviewees admitted that they strictly conform with their community and government regulations. Stakeholders have influences on interviewees' preferences in choosing heavy metal monitoring devices and techniques. Interviewee No. 2 claimed that *"the economic situation drives us to control costs. We consider technologies that are the most economical and in line with industrial standards."* In addition, innovations can be developed with society. Interviewee No.3 explained that *"we engage with a local engineering institute to provide opportunities for students to learn about wastewater management while the corporate also learned from them. We plan to become a smart industrial estate. For a more sustainable approach, we are using automated technology to help quantify and benchmark BOD and COD results from the database. This system also reports to the Department of Industrial Works. It would be advantageous, if SEAD could offer a real-time monitoring result. We are vigilant in monitoring wastewater qualities and we are ready for any surveillance audit."*

Findings from the proposed SEAD innovation adoption determinants concur with the literature. Firstly, the seller context had effects on new product adoption, and information exchange and feedback are keys to resolving conflicts (Rothwell 1994; Kotler, 1997). SEAD technology for toxic heavy metals contamination is new to consumers, therefore choosing communication channels to stimulate awareness should focus on understanding and having a mutual goal between sellers and buyers. Secondly, the buyer organization had effects on innovation adopting in terms of collaboration and networking. Unsuccessful technology integration jeopardized organization resources and reputations (Smith, 2013). Uncertain return on investment (Bierman et al., 2011), and technological threats (Yao et al., 2012) are barriers to RFID adoption in healthcare and wireless environmental monitoring systems. However, the successful resources sharing in R&D projects have proved sustainability in promoting RFID adoption in the healthcare industry (Katz & Shapiro, 1985). Thirdly, although, internal people characteristics may hinder technology adoption when users have negative attitudes (Venkatesh et al., 2003), if employees are familiar and become experienced with RFID technology, they will be more inclined to adopt it (Wang et al., 2010). Fourthly, superior, practical and valuable new technological attributes will lead to adoption. If a new technology is more advantageous and sustainable, users will be more likely to adopt it. The availability of compatible technologies impacts the potential adopter's interest in new technologies (Pham & Ho, 2015). Important technological attributes required from SEAD potential users are accuracy, standardization, sustainability, convenience, compatibility, minimized costs and simplicity. Lastly, the external environment plays a decisive role in adoption and sustainability. The findings concur with previous studies on NFC and RFID adoption (Museli & Navimipour, 2018; Wang et al., 2010). Technology adoption is a consequence of regulations, economic pressures, and societies that encourage sustainability in products and businesses. In short, it is vivid that seller, buyer organization, internal people, new technological innovation and external environment impact the diffusion of SEAD for heavy metal quantification. This study contributes to the understanding of sustainable industrial buyer innovation adoption (IBIA), which is influenced by related stakeholders. IBIA framework is an alternative hands-on navigator for understanding, creating and analyzing industrial innovations that reflect all fundamental foundations of sustainability, which are society (people), the environment (planet), and the economy (profit) (Thanabodypath et al., 2021).

4. Conclusions

The objective of this applied research was to preliminarily explore industrial users' hesitation with the adoption of the novel SEAD technology for monitoring sustainable environment from leading industry experts in Thailand. SEAD prototype was developed to assess user's adoption determinants as well as the product's performance.

The results demonstrated the practical application of SEAD for the determination of As(III), Cd(II), Pb(II) and Hg(II) from standard and real samples, which were in satisfactory agreement for ICP-OES determination. SEAD was developed and expected to analyze industrial wastewaters. SEAD's limits of detection (LOD) were 7.54 μg L^{-1}, 3.95 μg L^{-1}, 1.90 μg L^{-1} and 32.80 μg L^{-1} for As(III), Cd(II), Pb(II) and Hg(II), respectively. Whilst prospective users showed their intention to adopt SEAD, the future development of SEAD innovation relies on its performance improvements, especially in terms of interference elimination, detection limit, reproducibility and reliability. Once the targeted specifications are achieved, SEAD could potentially be benchmarked with conventional heavy metal determination methods using real industrial wastewaters.

Analysis of data from industrial user interviews revealed that five industrial buyer adoption (IBIA) determinants, which are seller, buyer organization, individual user, technological innovation and external environments impact SEAD adoption. This research contributes to the understanding of SEAD transition from scientific knowledge into sustainable technology and diffusible innovation, which aligns with UN SDG in monitoring clean water and sanitation, promoting industrial innovation and infrastructure, and ensuring the safety of life on land and below water.

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