# Human Practices

## THE STUDY OF STAKEHOLDERS' PERCEPTIONS TOWARDS THE IN-FIELD USE OF NPK MICROBIAL BIOSENSOR

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# ACRONYMS & ABBREVIATIONS

| | |
|---|---|
| AFCD | Agricultural, Fisheries and Conservation Department, HKSAR |
| EPA | The U.S. Environmental Protection Agency |
| EU | European Union |
| FHB | Food and Health Bureau, HKSAR |
| HKSAR | Hong Kong Special Administrative Region |
| HSEO | Health, Safety and Environmental Office, Hong Kong University of Science and Technology |
| GEM | Genetically Engineered Machine |
| iGEM | International Genetically Engineered Machine |
| NIH | The U.S. National Institute of Health |
| UGC-AoE | University Grant Committee – Area of Excellence |
| WWF-HK | World Wide Fund, Hong Kong |

# BACKGROUND

The HKSAR government proactively supported the modernisation of local agricultural industry and to maximise its contribution other than being a primary source of production. It is estimated that the new development would provide new employment opportunities for youngsters who aspire to develop careers in modern agriculture, conserve natural resources, and lastly better utilise land resources by means of sustainable agricultural practices (FHB & AFCD, 2014).

To maximise the contribution of modern agricultural practices, a possible and pertinent strategy is to build a pipeline for biotechnology and the related businesses. This gives a platform to fully utilise experts in botany, biotechnology, engineering, and business to deal with related agricultural issues namely improving soil quality, enhancing agronomic performance and safety assessments.

This year, HKUST-Rice Team of iGEM competition proposed to construct an NPK microbial biosensor for agricultural use. Biosensors for the detection of nitrate and phosphate ions had been developed by specific selection of the ions by enzymes in the 20th century (Moretto et al., 1998; Cosnier et al., 1998). Given the great capacity to adapt to adverse conditions and the ability to degrade new molecules with time, the use of microbes as biosensor was suggested (D'Souza, 2001). Thereby, whole-cell biosensors were also developed for the detection of nitrate, nitrite and phosphate ions by microorganisms (Reshetilov et al., 2000; Matsunaga et al., 1984).

Whole-cell biosensors which, although advantageous in measuring toxicity and bioavailability in soil and water, are nonetheless having low specificity as compared to biosensors containing pure enzymes (D'Souze, 2001). To specifically detect an analyte, genetically modifying the microbes is a conceivable way to form bioluminescent microbial biosensor. In the past few years, plentiful participants in iGEM competition were constructing biosensors by genetic engineering. These biosensors are targeting on a huge range of analytes with the use of various biocatalysts.

The primary focus of HKUST-Rice 2015 iGEM Team is to develop an NPK microbial biosensor to detect bioavailable NPK concentrations in soil, thus monitoring soil quality. It is believed that the application can be far beyond agricultural purposes, such as in water quality surveillance or sewage management. The team has no plan to reverse the preliminary design of the NPK microbial biosensor; this notwithstanding, the human practices team explores further including opinions from stakeholders who require soil or water management.

Presently, there is insufficient knowledge involving stakeholders and their opinion on using NPK biosensor. This is chiefly the case in situations with weak research environments on the study of stakeholders' perceptions, and in relatively emerging field in which there is insufficient evidence to categorically define them. The study of stakeholders' perceptions on using microbial NPK biosensor is seemingly in a new field. Deploying an exploratory research is a possible way.

To accomplish this purpose, the following research questions were addressed:

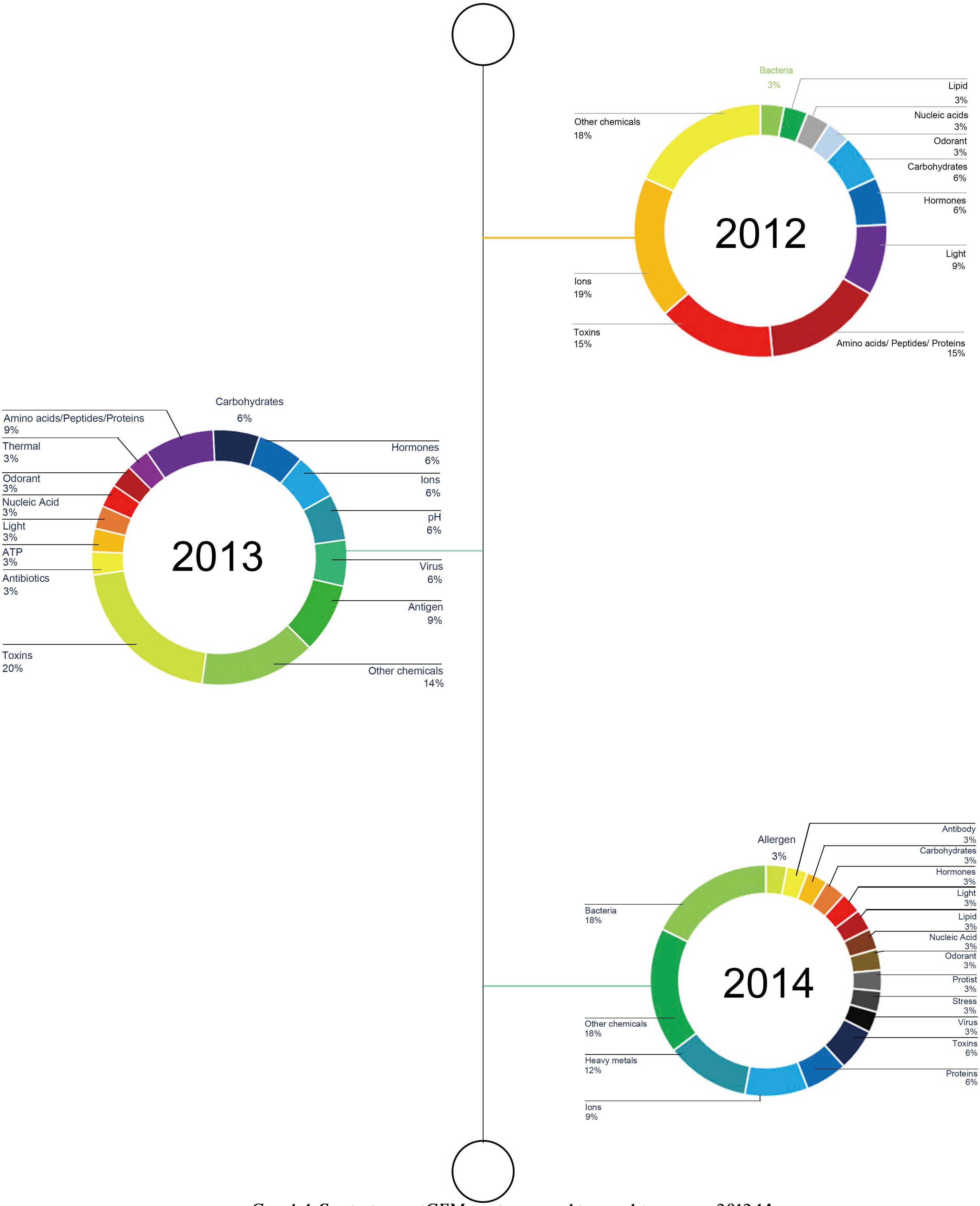
1. What are the perceived criteria regarding biosensor for NPK concentration detection?

2. What are the expected achievements in attaining sustainability in applying microbial NPK biosensor in their field?

3. How do perceptions of stakeholders change with the use of in-field microbial biosensor in terms of appropriateness of their settings?

4. How do perceptions of stakeholders change with the use of in-field microbial biosensor in terms of safety?

# What are they sensing?




Graph 1. Statistics on iGEM projects working on biosensor, 2012-14

# METHODOLOGY

The population for this study consisted of stakeholders including end-users, researchers and government officers. Since this was an exploratory study, qualitative in nature, a small sample was adequate to address the research questions (Creswell, 2007, 2009; Creswell & Clerk, 2007). It was desired these demographic segments be represented in the sample. These stakeholders are familiar with their workplace; the utilisation of their expertise would provide reasonable and valid comments on the application of microbial biosensor in their field.

The research questions were examined and validated through various exploratory experimentations. In this research, interviews were used to query the beliefs and perceptions of the participants. Taking a post-positivist paradigm (Guba & Lincoln, 1994), triangulation (Denzin, 1994), member-checking (Lincoln & Guba, 1985) and the audit trail (Lincoln & Guba, 1985) were used to validate the data collected.

The sample was drawn from Hong Kong, from multiple sectors (Table 2), where more people are aware of the research in genetic engineering and the possibility of its application in environment or in their field. The ultimate intent of the research was to provide a paradigm for understanding how people perceive the in-field application of microbial biosensor. The findings from this research could enable the researchers to respond to the appropriateness of applying the microbial biosensor in a particular field and to the safety concerns of the application, and provide a paradigm for other stakeholders to decide whether to apply microbial biosensor in their field. And if the stakeholders decide to apply microbial biosensor in their field, further research, for example quantitative analysis of their perception, based on this study's finding could help establish guidelines for promoting awareness of the pros and cons of the application of in-field microbial biosensor.

| Name | Stakeholders | Affiliation | Position |
|---|---|---|---|
| Mr. TO | organic farmer | e-Farm | farm owner |
| Mr. NG | organic farmer | Zen Organic Farm | farm owner |
| Mr. LAM | organic farmer | Fonley Organic & Friends | farm owner |
| Mr. WONG | organic farmer | Au Law Organic Farm | farm owner |
| Mr. YIP | organic farmer | Natural Network Farm | farm owner |
| Mr. TANG | organic farmer | Hande Farm | farm owner |
| Mr. CHAN | hydroponic farmer | iVeggie | person-in-charge of the iVeggie |
| Prof. H.M. LAM | agro-biotech professional | UGC-AoE Centre for Plant & Agricultural Biotechnology | deputy director of UGC-AoE Centre for Plant & Agricultural Biotechnology |
| Ms. S.M. CHIU | biosafety officer | HSEO in the HKUST | senior specialist of HSEO in the HKUST |
| Dr. S.C. NG | government officer | Agriculture, Fisheries and Conservation Department, HKSAR | conservation officer (ConO/B4) of the Agriculture, Fisheries and Conservation Department |
| Dr. Y.K. TAM | marine bio lab technician | Coastal Marine Laboratory in the HKUST | technician in the Coastal Marine Laboratory in the HKUST |
| Ms. N.Y. LAI | reserve officer in conservation zone | World Wide Fund For Nature Hong Kong | reserve officer of the World Wide Fund For Nature Hong Kong |
| Dr. T.W. TANG | Drainage service department chemist | Drainage Service Department, HKSAR | chemist of the Drainage Services Department |
| Dr. Joanne LEE | Algal bloom specialist from government | Agriculture, Fisheries and Conservation Department, HKSAR | fisheries officer (Aquaculture Environment) of Agriculture, Fisheries and Conservation Department, HKSAR |

Table 2. Sample Demographics

# LITERATURE REVIEW

## 1. Soil Management in Farms

In order to maintain the quality and quantity of the harvests, soil quality should be well-maintained over time. In Hong Kong, the Agricultural, Fisheries and Conservation Department (AFCD) offers soil tests to local farms as a part of soil management in its laboratory. The soil test covers the measurement of soil pH, electrochemical values, N, P, K and organic matter level by the corresponding measuring apparatus e.g. spectrometers (AFCD, n.d.). Farmers will receive a profile of the soil quality of their farms within one month. The bioavailable compounds should fall within the critical nutrient range (CNR). Excess in any nutrients brings about toxicity; on the contrary, deficiencies result in stunted growth (Fig. 3).

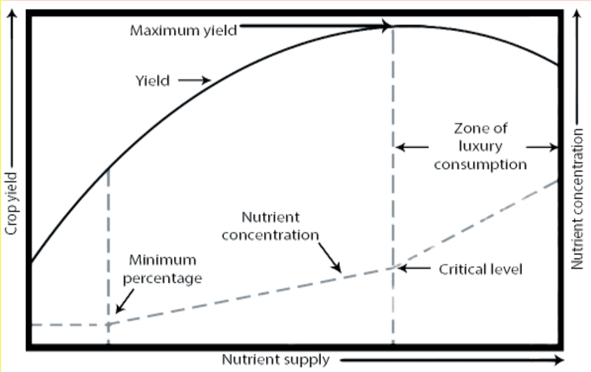



**Figure 3. Relationship between nutrient concentration in plant and crop yield**

In organic farming, soil management heavily rests on soil conservation and soil regeneration by virtue of managing crop residues, composting manures, and adding lime and other natural rock dusts to regulate pH and soil mineral concentration (Kuepper, 2000). This farming practice mimics a balanced, dynamic and living ecosystem within which nutrients and energy flow.

Contrary to organic farming, intensive farming emphasises "feeding the plant" more than "feeding the soil". A similar concept is applied to hydroponics; farmers are more concerned about the balance of nutrient solutions in order for optimising the quality and quantity of the harvest. For this reason, liquid fertiliser is constantly measured by the pre-installed probes to detect changes in pH, EC, macro- and trace elements (*Technology & Investment*, 2015).

In modern days, large-scaled intensive farms would consider using a real-time, site-specific, technological based management system, which is known as precision agriculture. This information-based management is beneficial in managing precise fertiliser applications, pesticide applications and irrigation by utilising at least one of the following datum: soils, crops, nutrients, pests, moisture, or yield for optimum profitability, sustainability, and environmental protection (Lowenberg-DeBoer, 2003).

## 2. Water Quality Monitoring and Sewage Treatment

Water quality monitoring is indispensable for aquaculture, securing human health and protecting habitats. In Hong Kong, AFCD has conducted routine water quality monitoring, including inorganic nutrients analysis and phytoplankton sampling at fish culture zones and offshore stations. The concentrations of inorganic nutrients viz., nitrate, nitrite, ammonium, phosphate and silicate ions, are determined by standard methods.

Similarly, sewage treatment improperly treated effluent will, eventually, pollute the marine ecosystem. The HK Drainage Service Department uses a flow injection analyser to determine phosphate and nitrate ions. The concentrations of the ions in the measurand are determined by spectrophotometer. The test results can be obtained in minutes and prompt actions can be taken immediately, if the concentrations deviated from expected.

The need for real-time, *in situ* water quality monitoring is increasing. The Ramsar site in Mai Po, Hong Kong, is threatened by the influxes of high organic and inorganic nutrients from illegal discharge of industrial and domestic sewage in close vicinity. Continuous water quality monitoring and surveillance projects are carried out by WWF Hong Kong (AFCD, 2011).

## 3. Biosensor Design

Researchers nowadays advance and improves biosensors in various aspects for instant precision, accuracy, reproducibility, lifetime, stability, simplicity, and online monitoring. The U.S. Environmental Protection Agency (2003) also released general requirements for biosensors used in environmental applications, which include, but are not limited to, the aforementioned characteristics.

Researchers have broadly availed microbial biosensors of environmental applications; examples include MicroTox (Strategic Diagnostics, SDIX) and BioTox (Aboatox). Nevertheless, only by genetic modification can microbes specifically detect target analytes, like pollutants, which generates detectable responses. Risk and uncertainty brought by GEM are big hurdles that genetic engineers had to overcome; the possibilities of accidental GEM leakage from biosensors or improper treatment of used GEM-containing biosensor should never be ignored.

## 4. Regulations

Local government and international organisations have adopted a legislative framework on the deliberate release of GMOs into the environment and the placing of GMOs on the market in accordance with the precautionary principle, which reads: When an activity raises threats of harm to the environment or human health, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically (The Global Development Research Centre, 1998).

Members of European Union are required to strictly follow the Directive 2001/18/EC and Directive 2009/41/EC, which detailed the procedures for granting consent for the deliberate release into the environment of GMO and the contained use of GM microorganisms. In 2011, the Genetically Modified Organisms (Control of Release) Ordinance, Cap. 607 is established and controls the release of GMO into environment and the transboundary movement of living GMOs in Hong Kong. The deliberate release of GMOs is prohibited, except for approval or exemption from the control of the Ordinance. In November 2013, the U.S. National Institutes of Health (2013) revised and released a ninety-seven-page long guide for research involving recombinant or synthetic nucleic acid molecules to which local institutes must oblige.

## 5. Sustainable Design Principles

Sustainability is a widely used concept. When it comes to material, product, process and system design and development, the major concerns are human health and the environment.

Engineers can access the *12 Principles of Green Engineering*, which provides a systematic and comprehensive framework for the maximisation of sustainability in a product (Anastas & Zimmerman, 2003). The more relevant and useful design principles for biosensors are as follows:

a. reducing inherent hazards with an inclusion of an in-device resolution to the inherent hazards;
b. designing a waste-free device; and
c. targeting on durable and renewable designs, but not immortality

As risk could be a concern to many stakeholders, service substitution could be a replacement of personal ownership of the device (Ryan, 2000). It is possible to deliver equivalent utility, and yet this becomes ideologically incoherent as biosensor is unique for its real-time and *in situ* detection.

# FINDINGS

## 1. Expected Achievements in Sustainability

### a. *Achieving Eco-Environmental Sustainability*

### *—FOCUS ON MY NEEDS, NOT ON THE FEE*

Stakeholders were asked about how they perceived the use of microbial NPK biosensor as an effective means to utilise available resources efficiently and responsibly.

Local organic farmers believed a microbial biosensing should be cheaper than contemporary soil testing methods, and the biosensor device should be tolerable and renewable so as to minimise the operation cost. They perceived a microbial NPK biosensor could constantly monitor the fluctuation of soil nutrient concentrations, such that humus can be composted to maintain soil quality; and hence, ensuring financial obligations over time are met.

*"If the biosensor can monitor the duration and the rate of the conversion process, and the amount of nitrogen being converted to nitrate, this can help with our farming. Or if the biosensor can tell us the amount of the bioavailable nutrients in the soil, it will be beneficial to agriculture."*

**Mr YIP, organic Farmer of Natural Network Farm, HK**

Similarly, in maintaining the water quality of *Gei Wai*, a traditional Chinese tidal shrimp pond, WWF-HK reserve officer in Mai Po agreed the biosensor device should be enduring and reusable to reduce the expenses on water tests.

She regarded a microbial NPK biosensor an alternative to observe the fluctuation of nitrate and phosphate ion concentrations in *Gei Wai*, such that researchers could monitor the relationship between the reduction of harvest and the changes in nitrate and phosphate ion concentrations; and thus, the device would be economically viable.

*"The harvests of Gei Wai shrimps and fish have reduced in recent years. Therefore, we want to find out the reasons and lift the production by managing the water quality."*

**Ms Nga-Yee LAI, Reserve Officer, WWF-HK Mai Po Marshes Wildlife Education Centre and Nature Reserve, HK**

## b. *Achieving Socio-Environmental Sustainability —CRADLE-TO-CRADLE*

WWF-HK reserve officer in Mai Po perceived the NPK microbial biosensor could possibly be a tool in understanding the ecology of *Gei Wai*. She perceived a microbial NPK biosensor would be useful for the surveillance of algal bloom, and understanding the *Gei Wai* ecosystem; thereby, conserving the Mai Po reservation zone.

*"There will be algal bloom when the water quality is not desirable, so we want to know whether it is related to the nitrate and phosphate content in water or not. If so, we can know the alarming level of these chemicals which helps the maintenance."*

**Ms Nga-Yee LAI, Reserve Officer, WWF-HK Mai Po Marshes Wildlife Education Centre and Nature Reserve, HK**

## c. *Achieving Socio-Economic Sustainability*

## *—ACCOUNTABILITY & RESPONSIBILITY ARE HARD*

The microbial biosensor should be viable for stakeholders, in particular, the ones in developing countries. Local testing facilities are not viable or accessible to them or more likely impoverished stakeholders may not have sufficient capital for sample tests.

*"The biosensor design should be creative; meanwhile, comprehensiv e, and practical. In poor farmers' point of view, the cost for soil tests could be unaffordable!"*

**Ms Christine CHIU, Senior Health, Safety and Environmental Specialist, HKUST, HK**

Christine valued the work ethics of researchers and designers the most. Her holistic views towards biosafety of microbial biosensors were particularly impressive. She pointed out risk managements on gene level, molecular level, human community level and ecological level should not be ignored, and it was the researchers and designers accountability and responsibility to safeguard human health and the ecosystem.

## 2. Perceived Usefulness

### a. *Effectiveness of Biosensor* —*ONE DEVICE, ONE UNRAVELLED SENSING*

Local organic farmers perceive microbial NPK biosensor, which can only detect specific compounds, as an insufficient measurement. They perceived an effective microbial NPK biosensor should give a complete profile of the N-, P- and K-containing compounds, including their concentrations and ratios. Furthermore, a sensor presenting an instantaneous concentration, rather than monitoring concentration change with time, was regarded as ineffective.

Prof Hon-Ming Lam, agro-biotechnologist, pointed out the practicality for an effective microbial biosensing. Here is the summary of his concerns: (i) in which bacterial growth phase is used for biosensing; (ii) the possibilities to produce quantitative results; (iii) whether the detection is truly linear; (iv) the ability of biosensing a wide range of concentrations of NPK in soil; (v) the advantages of NPK microbial biosensor over the contemporary physical tests.

As for the detection of marine environment, a technician in the university marine laboratory worried the detection environment, in which innumerable factors present would interfere the accuracy of biosensing.

*"Interferences from hundreds of unknown substances or variability of surrounding environmental conditions in the field are also concerns of users."*

**Dr Yin-Ki TAM, technician of Coastal Marine Laboratory, HKUST, HK**

Furthermore, he perceived that the application of microbial biosensor should be standardised, so that the procedures and results could be reproducible and recognised.

*"In order to have our data published or trusted, they must be generated by widely accepted 'standard methods' of detailed QA/QC procedures so that other parties can repeat your steps and obtain the same results. These methods are standardized, published and suggested by authorities of high reputations."*

**Dr Yin-Ki TAM, technician of Coastal Marine Laboratory, HKUST, HK**

### b. *Efficiency of Biosensor* —*NEVER WASTE ANY TIME YOU CAN SPEND RESTING*

Speed is not a concern for most of the local organic farmers. They understand it takes time for microbial fermentation of the compost. They perceived an instantaneous presentation brings no significance to monitoring fermentation and the change in soil quality over time.

*"Organic farmers understand that farming requires time. For intensive farming, time may be an issue. We understand that the [nutrient] cycles require time [to complete]. Even if you tell me that the sensor is fast, like 60 seconds, or 60 minutes, the speed is really not that needed."*

**Mr. TO, organic farmer of e-Farm HK, HK**

Hydroponic farm operator even doubted the efficiency of the microbial biosensor for the detection of the ion concentrations when compared to automated detection facilities in his hydroponic farm.

"It is not efficient to make biosensors for studying ion distribution. It is much useful to use X-ray fluorescence imaging to obtain a complete profile of ions in soil or in plants than using microbial biosensor."

**Prof Hon-Ming LAM, Associate director, Institute of Plant Molecular Biology & Agricultural Biotechnology, CUHK, HK**

Similarly, when an agro-biotechnologist asked about the possibility of using microbial biosensor for measuring the soil ionomics, he perceived it would be an inefficient use.

*"Our farm monitors the nutrients level by detectors connected to the computers. The automated system adds back pre-mixed chemical fertilisers immediately and accordingly, in response to the changes of pH and electricity conductivity in the fertiliser tank."*

**Mr. CHAN, iVeggie—hydroponic farm operator, HK**

On the contrary, conservation officer valued the efficiency in generating data and data processing for analysing the nitrate and phosphate concentrations in the traditional tidal shrimp ponds due to the limited manpower.

## 3. Changes of Perceptions

Stakeholders are informed about biosensing involved the use of GEM, which could possibly directly or indirectly contact with the medium. Most stakeholders had reservations or negative perceptions regarding the application of NPK microbial biosensor in their field.

### *a. Appropriateness of Setting*
### *– THE MICROBIAL BIOSENSOR TOPS CONCERNS*

Overall, the stakeholders were most concerned with the appropriateness of using GEM or the GEM-containing device in their field or whether it would be suitable to place the GEM-containing in their field. Some organic farmers questioned if GEM an appropriate device in organic farming, regardless of its design. They believed the application of in-field GMO-containing devices violated the principles of organic farming.

> *"Well, I think it does go against the values of being organic to some extent because you do genetically modify the bacteria right? Are there any non-modified bacteria that can do the same thing? I mean certainly I understand it is not going to directly affect the plants, but still. It's a difficult question."*
>
> **Mr. TANG, organic farmer of Heaven & Earth Organic Farm, HK**

As in natural reservation zone, conservation officer hesitated and pointed out the possibility that the GEM-containing device would be treated as inappropriate in reservation zone; in addition she mentioned parties, including the government and the public, that would exert pressure on these novel, and yet untested, devices for in-field research.

## b. *Perceived Risks*

## *— MICROBIAL BIOSENSOR: SABOTEUR OF THE STATUS QUO?*

Even if it could be an appropriate use, stakeholder questioned on the esoteric character of in-field GEM. They were aware of the risk of using GEM in their field and balancing the perceived risk against the perceived usefulness.

All organic farmers were hesitated and/or resisted to adopt an in-field microbial biosensor. Some worried about whether GEM would be released in soil for direct measurement or by accident; and subsequently, their effects, including but not limited to bacterial gene transfer.

> *"If it is harmful, we will not use it as we have to consider the safety and health of the public."*
>
> **Mr. AU, organic farmer of Au Law Organic Farm, HK**
>
> *"You must not release the genetically engineered bacteria to the environment because they contain antibiotic resistant gene. Then, how are bacteria contained?"*
>
> **Prof Hon-Ming LAM, Associate director, Institute of Plant Molecular Biology & Agricultural Biotechnology, CUHK, HK**

Chemist in Hong Kong Drainage Service Department was suggested using NPK microbial biosensor for in-the-tank detection, he believed the quantity of microbes in the device would be in small quantity and could be handled by disinfection system for any leakage, but he questioned what happened if the leakage occurred after disinfection.

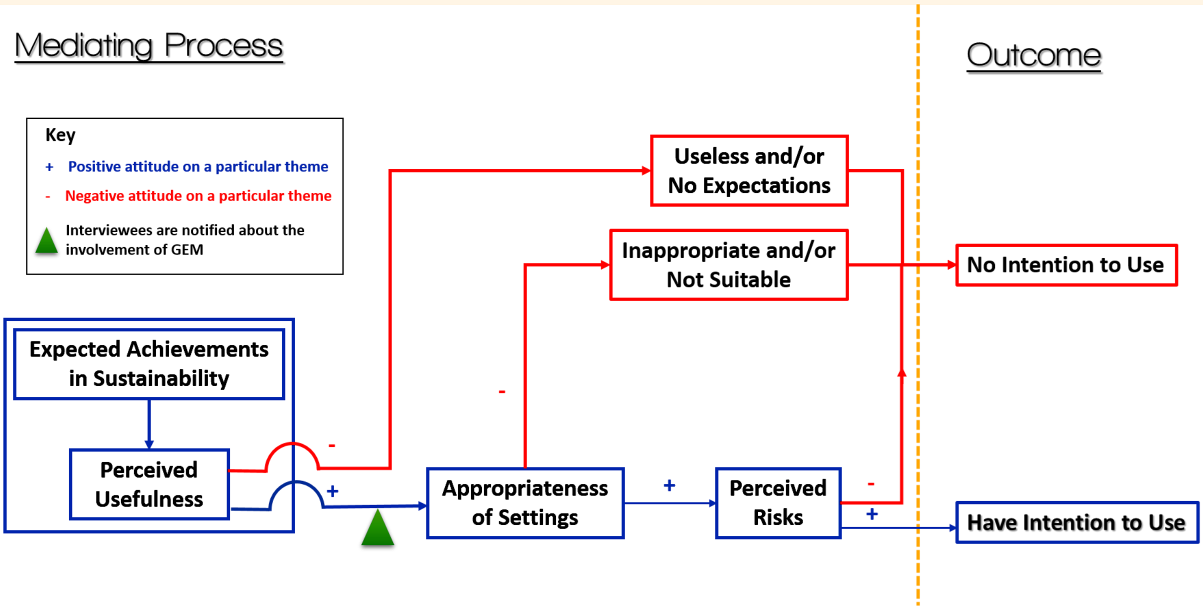
> *"I guess its quantity might be small and could be handled by the disinfection system. Therefore, its impact might not be that significant. Having said that, if [leakage] happened after the disinfection step, then it would be a disaster."*
>
> **Dr. Tin-Wu "Daniel" TANG, chemist of Hong Kong Drainage Service Department, HK**

# INTERPRETATION

The participants' perceptions and emergent themes are consistent with the literature review. The literature suggests that farmers, mariculturists or environmental conservationists require management scheme for soil or water quality monitoring, while many of the interviewees have deployed testing methods in their fields. Moreover, stakeholders concurred the annual soil or water sample tests were offered by the government department, and only Mai Po Nature Reserve applied spectrometer and probes for quick tests bi- or tri-monthly.

Literature suggests the soil management in organic farm is included in their farming practices, and although the literature does not emphasise the needs of soil tests in organic farming, the interviewed organic farmers agreed that their management scheme is to replenish the soil nutrients by composting humus or organic fertilisers based on experiences and observations, instead of relying on the annual soil test results. Finally, the literature mentions the deliberate release of GEM is globally prohibited; an individual case, for example applying for an in-field use of GEM-containing biosensor, is subjected to approval by the local government and/or international organisations. Researchers and businesses have responsibility to consider the sustainable use of the GEM-containing devices, the risk concerns and the corresponding resilient methods.

In the study, age and sex are not under our considerations. Whilst possible external variables, for example workplace, education, prejudgements and experiences, would affect their expected achievements in sustainability, and nonetheless the study focuses on the level of studying core values, attitudes, and beliefs.




Graph 4. The paradigm of the interviewees' perceptions on the in-field application of NPK microbial sensor

The paradigm below illustrates interviewees' perceptions on the in-field use of NPK microbial biosensors in their field (Graph 4). For the most part, initial perceptions were related to how they believed those features in helping them achieve sustainability in their field and how they perceived the features that a biosensor should acquire as being an effective and efficient tool.

While most stakeholders still agreed that a biosensor possessing the expected characteristics would be an effective and efficient means to lowering their operation cost, reducing their manpower, knowing the test results quicker, and thereby making immediate strategy to manage soil or water, etc.; followed by notifying the involvement of GEM in the device, stakeholders began to consider further, from how the desired biosensor could help them in their field, to how the desired biosensor actually fits into their field. They believed the design should be suitable to their field and considered its appropriateness. Ultimately, stakeholders reflected on potential risks; at the same time, they balanced the perceived benefits and perceived harms of using the microbial biosensor.

Most stakeholders' perceptions follow a single path and the majority has no intention to use for the following reasons: (i) the biosensor is useless in their field, (ii) the biosensor is unable to achieve sustainability in either aspects, including economics, social and environmental, (iii) the biosensor is an inappropriate device in their field, (iv) the biosensor is not suitable to be used in their workplace, and (v) the perceived risks of the microbial biosensor outweighed the original perceived benefits.

This research could help researchers decide if their design truly meets the need of different stakeholders; and if so, how to apply the biosensor in order for achieving sustainability, and maximising its efficiency and effectiveness, while minimising the risks.

Literature points out the advantages of using microbial biosensor for specific, accurate and precise detection of the targeting molecule; but, there is no consensus in the literature regarding microbial biosensor as a more advantageous method of detecting NPK concentrations in soil or in water than contemporary ones.

Specifically, some stakeholders felt that they were unsure or did not want to include microbial devices in their field; some felt that it would be a risky device. This may be due to their prejudgments towards GEM. This research gives insights and provides a framework to investigate the unintended consequences for improper use or accidents. Interviewees' perceptions can aid researchers in developing research that would further delineate policy and practices for the use of GEM-containing device.

Additionally, since there is no consensus in the literature as to which situations, locations, and specific factors make the application successful, possible users should be informed of the intended uses of the whole-cell biosensor or GEM-containing biosensor, and how to maximise its effectiveness. Lastly, education provided by researchers could inform stakeholders about the purposes and limitations of the applications, as well as how risk concerns are addressed by the developers' policies. It may be effective for developers to sporadically collect data regarding the feedback of users and the functioning of the biosensor.

# LIMITATIONS

The interview process was informative with respect to individual opinions representing the perspectives of key stakeholders invested in safe, accurate, and effective soil detection methods. These analyses provide an essential qualitative component to a study of perceptions. However, one crucial limitation of this study involves a lack of quantitative analysis. Without a systematised approach to collecting uniformly coded responses, this study demonstrates limited power. Furthermore, a relatively small sample size precludes the use of statistical methods to present numerical confirmation of the findings presented here.

The study includes a wide variety of perspectives but does not claim to offer an exhaustive representation of all participants in the agricultural industry. For instance, fertiliser companies from Hong Kong could not be found to offer comments. Other possible stakeholders who could not be reached for comment include the disseminators of agricultural literature to which farm operators and others refer as well as agrochemical companies experienced in the production and consumption of genetically modified products. The potential stakeholders who would be affected by the implementation of microbial biosensors constitute an intricate network; participants in this network need to be further mapped out in subsequent studies.

Additionally, this study initially attempted to represent an international comparison between potential stakeholders' perceptions in both Hong Kong and in the United States. However, when asked to offer input on current soil detection technologies in the field as well as opinions on the proposed microbial biosensor, very few U.S. stakeholders responded to requests for interviews. After two attempts at making contact, new stakeholders were sought, but with similarly unsuccessful results. Reviewing a total of three responses (from a graduate student in soil science, a farmer, and the owner of a small pest control business) led us to hypothesise that most soil detection in U.S. farms (specifically in the state of Texas) occurs via chemical tests performed by soil science laboratories. In this method, farmers and other stakeholders collect the soil samples they want to be analysed and submit them to a soil lab associated with a centralized agricultural extension service. The responding stakeholders indicated this was an extremely reliable, efficient, and cost-effective method for analysing nutrient levels in the soil. (Furthermore, these same labs are able to determine whether diseases or pests are affecting a particular plant or crop from similarly collected samples.)

Existing soil detection practices appear to satisfy the current market of stakeholders. To our knowledge, no mention of microbial biosensing technologies appeared in the educational literature distributed by a state-wide agricultural extension service. (Many stakeholders rely on these services to keep abreast of new and improved agricultural technologies.) This same agricultural extension service that offers relatively low-cost soil testing to its customers thus would need to distribute materials on microbial biosensors in order to make a greater impact on stakeholders. As a result, we attribute the low U.S. response rate and relatively high degree of unfamiliarity with microbial biosensors to a lack of available literature and other educational resources.

# FUTURE RESEARCH

Knowing the limitations of this study, the results presented here and the conclusions drawn from them offer a well-founded point of departure for future studies. Possible topics include:

1. An investigation of what proportion of the general population perceives biosensors as a risky endeavour with respect to the agricultural goods they consume, especially food products.
2. Projected cost differences between field-tested soil sensing devices--the proposed microbial biosensor compared to a chemical-based test kit.
3. A study on differences in time between sample collection and useful results for both the proposed microbial biosensor as well as traditional chemical soil detection methods. How important is this time point to the stakeholders?
4. The implications of microbial biosensing technology on the existing agricultural workforce. Would the implementation of the proposed device reduce the need for additional manpower? In other words, how does the use of a microbial biosensor affect perceptions of job availability in the agricultural field?
5. The role of precision agriculture in current farming practices. Could a microbial biosensor be applied to improve these large scale measurements?

These proposed directions for future research need to be studied using a well-focused combination of qualitative and quantitative approaches grounded in social science theory.

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