Re-engineering Agricultural Innovation in Southeast Asia (RAISE-Asia)

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ABSTRACT

Feeding the growing global population and reducing poverty require innovative approaches in agriculture and food systems to sustain the planet's health and food requirements. Sustainable development can be achieved by generating new knowledge and translating them into use through innovation process. A customer-oriented technology readiness level (COTRL) tool is presented to re-engineer agricultural innovation by systematically assessing new agricultural technologies with customer input and ensuring that the early design of the scientific research already has the end-products in mind. The COTRL methodology will integrate research, prototyping, and commercialization efforts and facilitate a disciplined and impactful innovation process. It will guide researchers and scientists, research managers and coordinators, funding agency program managers, policymakers, and other personnel involved in bringing scientific discoveries to market for societal impact. The COTRL framework can be used to strengthen the collaboration among academia, research institutions, networks of excellence, and the private sector in the ASEAN to create an effective ecosystem for manpower and structural capability development, knowledge sharing, and business development within and across member states.

Keywords: innovation, technology readiness level, voice of the customer, agriculture and food systems, COTRL
JEL codes: O3, O31, O32, O33, O34, O35, O36

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INTRODUCTION

The global population reached eight billion in 2022 and is estimated to reach 9.7 billion in 2050 (medium-fertility scenario) (UN n.d.). Additionally, food consumption per person has increased from an average of 2,360 kcal/person/day in the 1960s to an average of 3,000 kcal/person/day by 2030 (Bruinsma 2003). The total global food demand is expected to increase by 35–56 percent between 2010 and 2050 (van Dijk et al. 2021). Feeding the growing global population and reducing poverty are challenges of unprecedented dimension (Wang, Meybeck, and Sonnino 2019). Thus, innovation in agriculture and food systems (AFS) is crucial to sustaining the planet's health and food requirements. Innovation, a process that translates ideas into practical reality with significant positive impact and value to society, is a cornerstone of any modern economic enterprise, a critical driver of sustainable development, and integral to any nation. For example, increased productivity arising from innovation and changes in technology is the main contributor to economic growth in US agriculture (USDA ERS 2024a). The major drivers include innovations in animal and crop genetics, improvements in operation management, and changing farm sector structure (USDA ERS 2024b).

Agricultural productivity depends on investments in research and development (R&D) (Cai, Golub, and Hertel 2017). Governments have invested heavily in research, generated ideas, and built prototypes. Some nations invest in research as high as five percent of their GDP (World Bank Group 2024). However, many investments have not successfully brought these research discoveries to market. The lag between research and impactful products sometimes takes years, and research results may reach intended users too late (Wang, Meybeck, and Sonnino 2019). The challenges of food resiliency (supply, security, and safety), water scarcity (quality and quantity), environmental quality, and sustainable health require transformational innovations. Agriculture is inherently complex and increasingly dynamic due in part to changing international trade and market demands, changing consumption patterns and shifting demographics, changing food production and distribution centers along value chains, changing food safety standards, and changing climatic patterns (Wang, Meybeck, and Sonnino 2019). Addressing this complexity requires agricultural innovation to be strategic, forward-thinking, and intentional with unconventional approaches. A user-centered innovation process can accelerate technological advances in meeting the needs of the present without compromising the ability of future generations to meet their own needs. It will bring new products, processes, and forms into social and economic use to add value or disrupt existing ecosystems, increase competitiveness, improve resilience to shocks, and contribute to the achievement of WHO's sustainable development goals (WHO 2024), including One Health, food and nutritional security, economic stability, and environmental quality (Wang, Meybeck, and Sonnino 2019).

Sustainable development can happen by generating new knowledge and translating them into use through the innovation process (FAO 2017). However, even though new agricultural technologies may be promising and create new possibilities, the development and implementation of new technologies are complicated (Vik et al. 2021). The innovation process is generally divided into three phases: (1) ideation, (2) R&D, and (3) acceleration or commercialization (Klitsie, Price, and De Lille 2019). The most challenging phase is R&D, a period where ideas are translated into prototypes and validated in real-world scenarios, and thus requiring increased funding and multidisciplinary skills. This is the period of the valley of death (VoD), defined as the transition from ideation to commercialization (Ellwood, Williams, and Egan 2022), from breakthrough invention to commercial application, from opportunity discovery (invention) to product launch (Klitsie, Price, and De Lille 2019), or from the lab to the market (Gbadegeshin et al. 2022).

TECHNOLOGY READINESS LEVEL (TRL)

To systematically guide innovation in science and technology, the US NASA developed the Technology Readiness Level (TRL) in the 1970s to assess and communicate the maturity of new technologies and to compare maturity among different types of technologies with rating going from 1 (initial invention) to 9 (product launch) (NASA 2024; Salazar and Russi-Vigoya 2021). NASA recognized that in a world of complex system development, it was necessary to develop a common frame of reference to communicate the maturity of technology, its progress, its risks, and technology readiness that could affect technical, cost, and schedule. The TRL was developed to understand the technological maturity measure of performance, reliability, durability, and operating experience in the expected environment, and could be assigned at the system, subsystem, or component level, with each level having criteria to determine if the technology was ready to mature to the next level (Salazar and Russi-Vigoya 2021). Since its development, the TRL has been adapted and modified by many organizations, including the US Department of Defense (DoD) (Institute of Medicine and National Research Council 2014), US National Institutes of Health (NIH 2019), US Medical Countermeasures (Medical Countermeasures 2024), US Department of Agriculture National Institute of Food and Agriculture (USDA NIFA 2018), European Association of Research and Technology Organisations (EARTO 2014), and many more.

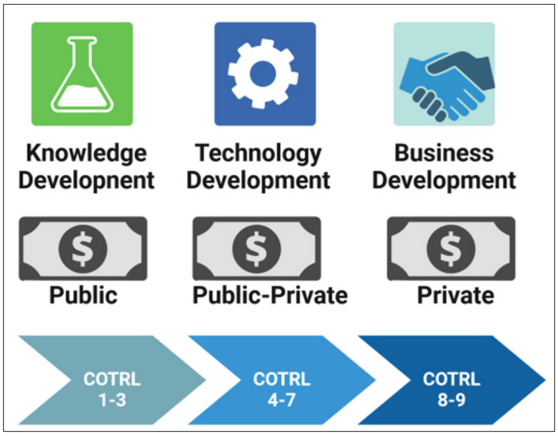
The TRL establishes technical feasibility, but technology readiness alone does not guarantee market acceptance and customer use. Successful product development is finding a balance among technical feasibility, user desirability, and business viability (Klitsie, Price, and De Lille 2019). User desirability is based on understanding the customer's needs and problems through customer discovery. A customer-driven engineering method that has been successful in bringing the customer's voice into product design is the Quality Function Deployment (QFD). The QFD is a quality management system that brings the voice of the customers (VoC) into the product development process from conceptual design to production (Cristiano, Liker, and White 2000; Chan and Wu 2005). It links the voice of the customer to the voice of the technologist (Chan and Wu 2005). Customer needs and values define customer requirements (CRs) and translate them into engineering characteristics (i.e., ECs) to maximize customer satisfaction within the budget constraint. Customers' perception of CRs as the starting point directly influences the subsequent procedures of technology development and, eventually, resource allocation (Shen et al. 2022). The QFD coordinates organizational skills to design, manufacture, and bring to market products that customers want to purchase. Marketing people, design engineers, and manufacturing staff work closely together, starting at product ideation to ensure that VoCs are carried through to a customer-oriented final product (Hauser and Clausing 1988). VoC helps clarify marketability, including defining the market niche and market size. Customers can be grouped into meaningful hierarchies or categories and engaging every group ensures that proposed solutions solve real problems for real people. This process saves time and resources and guides the creation of products people genuinely want (SBTDC 2024).

CUSTOMER-ORIENTED TRL (COTRL)

This paper presents the concept of a novel customer-oriented TRL (COTRL) to re-engineer innovation in the AFS, leading to the creation of marketable products that customers want in the fastest possible time. The COTRL adapts TRLs from other sectors (e.g., DoD [Institute of Medicine and National Research Council 2014] and USDA NIFA 2018) to make it agriculture-centric and combines it with VoC feedback throughout the innovation process. VoCs in COTRL include not only the end users (e.g., farmers, farm associations, cooperatives, medical professionals, consumers, and governments) but also market assessors, food processing and supply chain operators, regulators (e.g., safety laws and guidelines), intellectual property reviewers, manufacturers, technology component suppliers, and more. The information generated through the VoC changes as product development progresses. In the latter stages, VoC will include the technology's patentability (patent, copyright, and trademarks), manufacturability, and component supply chain issues, such as scale-up processes and peripheral component availability. Thus, COTRL is a holistic management tool to systematically assess technology readiness of new agricultural technologies with various VoC inputs along the development process. It will be a tool to seamlessly integrate research, prototyping, and commercialization efforts. It will facilitate a disciplined and impactful innovation process where the early design of the basic scientific research already has the end-products in mind.

The agricultural innovation effort can be categorized into three main stages of development: (1) knowledge development: basic research and proof of concept (TRL 1-3); (2) technology development: technology prototyping, validation, and scale-up (TRL 4-7); and (3) business development: product launch and business creation (TRL 8-9). COTRL thus implies that TRL 1-3 assessments are done with TRL 8-9 in mind.

Figure 1. A schematic of the innovation process to transform ideas into products that impact society



Notes: The innovation process includes knowledge, technology, and business development stages. In each stage is the technology readiness level assessment and potential funding sources.

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Figure 2. The Valley of Death occurs between TRL 1-3 and TRL 8-9 during the innovation process

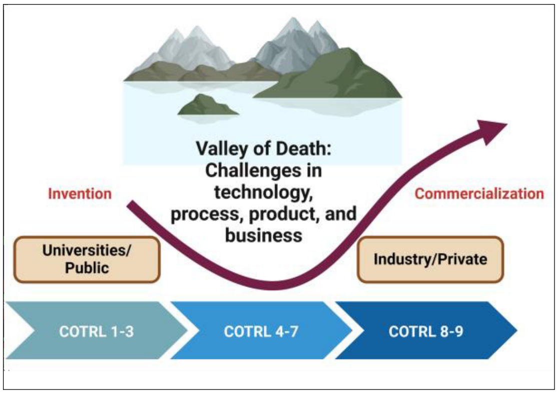

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Figure 1 illustrates the integration of the innovation process, the TRL assessments, and funding sources. The actors for TRL 1-3 are usually academic institutions and government research labs, while the actors for TRL 8-9 are business companies. TRL 4-7 requires collaboration between academia and businesses. The private sector, public sector, and end users are connected at TRL 4-7 to achieve a higher success rate of customized innovation meeting users' needs. This is also the stage where protocols are established to examine, file, and protect intellectual property rights and facilitate technology licensing. The focus is on technical viability, market/user research, and business case development (Klitsie, Price, and De Lille 2019). Figure 2 illustrates the occurrence of VoD during the R&D phase. VoD challenges include concerns about sufficiency in technology innovation, process, product, and business/financing. Table 1 presents the COTRL methodology for AFS, adapted from DoD (Institute of Medicine and National Research Council 2014) and USDA NIFA 2018, TRLs and QFD's VoC. The novel approach is expected to generate innovative ideas based on customer-oriented design principles rather than the innovator's traditional expertise (Shen et al. 2022). Customer-oriented innovation enhances product adoption and customer satisfaction.

Table 1. Customer-Oriented Technology Readiness Level (COTRL) for agriculture and food systems

Level	Agriculture and Food Systems	VoC	General Description
1	**Challenge/opportunity identification:** Potential technologies are explored. Examples include paper studies of a technology's properties.	Farmers, operators, cooperatives (coops)	The industry or other users face challenges and the need for a new kind of innovation.
2	**Solution or approach formulation:** Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytical studies.	Farmers, operators, coops	Publications or other references outlining the application being considered and providing analysis to support the concept. Estimate the value of the innovative solution compared to the existing technologies and where the solution fits in the overall supply chain.
3	**Proof-of-concept feasibility:** Active R&D is initiated, including analytical studies and laboratory studies to physically validate the analytical predictions of technology components.	Farmers, operators, coops, market evaluators, regulators	Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. Screen technological innovation to demonstrate its potential added value. Conduct customer discovery to assess potential market niches and size.
4	**Technology prototyping and validation in the lab:** Essential technological components are integrated to establish compatibility.	Farmers, coops, market evaluators, competitors	Experiments conducted to determine the performance of the technology. Provide an estimate of how the technology test results differ from expected system goals.
5	**Technology validation in operation:** Essential technological components are integrated with reasonably realistic supporting elements to be tested in a simulated environment.	Farmers, competitors, intellectual property (IP) evaluators	Conduct field-scale production trials or on-site technology assessments to determine actual production costs, resource usage, market potential, or other technical limitations, including market acceptance. Assess IP.
6	**Technology demonstration in operation and scale-up:** A representative model or prototype system is tested in a relevant environment to validate commercial acceptance.	Farmers, competitors, IP evaluators, scale-up manufacturers	Results from a laboratory testing of a prototype system near the desired configuration. Ensure components are available and can be sourced for full-scale production.
7	**Technology demonstration in practical settings:** Scaled-up prototype near or at the planned operational system (e.g., farm settings).	Farmers, users, operators, manufacturers, investors	Results from testing a prototype system in an operational environment (e.g., farm settings)
8	**System qualification:** The technology is proven to work in its final form and under expected conditions, and commercial usefulness is established.	Farmers, manufacturers, supplychain providers, investors	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements.
9	**System proven in practical settings:** Actual application of the technology in its final form and under mission conditions.	Business developers, investors	A full array of private and public sector services is available to support system-level production, handling, distribution, and markets across entire supply chains.

Sources: Institute of Medicine and National Research Council (2014); USDA NIFA (2018)

RE-ENGINEERING AGRICULTURAL INNOVATION IN SOUTHEAST ASIA

Southeast Asia (SEA) is increasingly becoming a significant producer of agricultural products in the global market. The SEA agriculture sector includes farming, fishing, and forestry due to their long coastal lines, large and diverse ocean ecosystems, and tropical weather. Despite increasing industrialization, the agriculture sector remains a significant contributor to the region's economies. Vegetable oil, palm oil, coffee, and rice are exported in large volumes from SEA. For example, Malaysia and Indonesia account for 90 percent of the world's palm oil exports during the period 2019–21. Vietnam is the second-biggest exporter of coffee. More than 40 percent of rice imported to the European Union comes from SEA, such as Vietnam, Thailand, Myanmar, and Cambodia. SEA is also rich in marine resources, with Indonesia, Vietnam, Thailand, and the Philippines being top seafood exporters globally. SEA exports around 20 percent of all wooden furniture products globally (ARC Group 2022). Increasing exports requires new and innovative technologies in the agriculture sector, allowing the Association of Southeast Asian Nations (ASEAN) to contribute to the world's food requirements collectively. Every ASEAN member state (AMS) is committed to sharing knowledge and research developments and translating research outputs into implementable solutions that address the real-life problems faced by its people. The COTRL framework can facilitate the implementation of such commitment within and among ASEAN countries. As an ASEAN collaborative platform, it can enable technology transfer and commercialization and connect the public and private sectors and end users to codesign practical solutions customized to meet the needs of their people. COTRL can be a collaborative platform to establish protocols for filing, examining, protecting, and enforcing intellectual property rights, such as patents, designs, plant varieties, copyrights, and trademarks, and facilitate the process in which the technology can be acquired or licensed for the product to be manufactured in another member state or jurisdiction. It can also be used in establishing protocols for protecting intangible assets, such as local knowledge and indigenous resources for business purposes. It can be used to strengthen the collaboration among academia, research institutions, networks of excellence, and the private sector to create an effective ecosystem for manpower and structural capability development, technology transfer, and commercialization. Finally, COTRL can be used as a collaborative platform to integrate science, technology, and innovation efforts within and among AMS (ASEAN 2024). Table 2 lists the potential users of COTRL and how they may utilize the tool to advance innovation in AFS.

ILLUSTRATION OF COTRL

The next section describes a case to illustrate the COTRL methodology in the development of a smartphone-enabled nanoparticle-based biosensor for onsite monitoring of pathogens, especially *Salmonella enterica*, in poultry (chicken and turkey) farms and meat products.

TRL 1: Challenge/Opportunity Identification

Brief problem statement. Rapid detection of pathogenic bacteria frequently associated with food is critical for controlling and preventing disease outbreaks. Specifically, onsite pathogen detection is presently lacking in ensuring public safety in the consumption of poultry products.

Significance. Disease outbreaks related to contaminated food make millions ill and lead to numerous deaths each year. A report published by the World Health Organization showed 420,000 deaths from 600 million foodborne infections annually (Havelaar et al. 2015). Some common bacteria that lead to food-related illnesses include *Salmonella enterica*, *Escherichia coli*, *Listeria monocytogenes*, and *Bacillus cereus*, among others (Huang et al. 2016; Liu et al. 2019). *E. coli* and nontyphoidal *Salmonella enterica* (NTS), ubiquitous in poultry products, are leading causes

Table 2. List of potential users of the customer-oriented technology readiness level (COTRL)

Users of COTRL	Use of COTRL
Researchers/scientists	Guides research activities from ideation to product launch and facilitates planning basic scientific research with the end-products in mind
Research managers and supervisors	Systematic assessment of research activities and new technologies with customer input at the early stage of technology development
Funding agency program managers and reviewers	• Systematic review and monitoring of research investments and outcome assessments of funded research projects • Determine technology readiness for next level of funding • Assess potential societal impact of research projects
Policymakers	Systematic assessment of structural support to advance science and innovation and improve return on investments for the country
ASEAN member states (AMS)	• Collaborative platform connecting member states to codesign practical solutions for the country and the region • Facilitate technology transfer and commercialization; establish protocols for filing, protecting, and enforcing intellectual property rights • Strengthen the collaboration among academia and research institutions within and among countries.

of foodborne diseases worldwide and significant causes of septicemia, meningitis, endocarditis, and osteomyelitis (Ao et al. 2015; Fuche et al. 2016). The NTS is responsible for 94 million infections and 155,000 deaths worldwide annually, 86 percent of which are estimated to be foodborne (Fuche et al. 2016). Of those hospitalized with foodborne illness, 29–34 percent develop bloodstream infection (BSI) with high morbidity and mortality rates and extended hospital stays (Ahn et al. 2022; Fuche et al. 2016). Every hour of delay in detection and antimicrobial therapy in BSI patients result in a 7.6 percent increase in the death rate (Kumar et al. 2006).

Available detection technologies. Culture is the gold standard in many microbial guidelines; however, the enrichment takes time (from days to weeks). Current methods of bacterial enrichment include culture, centrifugation, filtration, microfluidics, and immunomagnetic separation (IMS). Polymer-based partitioning systems are a few examples of physical methods that have been proposed in the past (Benoit and Donahue 2003). Automated bacteria concentration and recovery systems have also been suggested but require multiple filters and a complicated process (Zhang et al. 2018). Centrifugation is simple, but it could pellet not only the bacteria but also some sample matrix that may inhibit detection methods, making it inefficient (Ruban, Sharada, and Banday 2011). Filtration removes matrix components that may interfere in subsequent pathogen detection; however, challenges include clogging of filters and poor recovery of microorganisms from the filter. Microfluidics-based bacterial separation is gaining popularity, but the complexity of most samples remains one of the biggest barriers to rapid uptake of microfluidics (Needs et al. 2020). The IMS has been successfully used in microbial separation in food (Wang et al. 2011; Kraft et al. 2017; Chen and Park 2017; Jadeja, Janes, and Simonson 2010). However, binding between antibody and antigen depends on their affinity, antigenic expression, and the physico-chemical properties of the suspending sample matrix. IMS is also costly, requires antibody production and refrigeration for storage, and in many cases, a technique optimized for one matrix or microorganism is not readily adaptable to others (Ruban, Sharada, and Banday 2011). Coating magnetic particles with bacteria-specific phages has also been reported (Kretzer et al. 2007). Multiple examples exist in literature where phage-based magnetic particles have been used for pathogen separation from both water and food products (Wang et al. 2016b; Kretzer, Schmelcher, and Loessner 2018). Coating of magnetic particles with phages may prove to be a tedious process and can take long hours (Wang et al. 2016a). Furthermore, issues related to desiccation and low density of capture elements on magnetic particles are significant challenges that need to be addressed (Bayat, Didar, and Hosseinidoust 2021).

Polymerase Chain Reaction (PCR) and real-time PCR (RT-PCR) have been developed for detection (Hoorfar 2011). Still, they are expensive, require lab personnel and a facility, and are prone to reaction inhibition due to matrix interference. Many of these techniques cannot deliver reliable results just in time to efficiently separate products in poultry slaughterhouses to the fresh poultry market or further processing that may include cooking to destroy pathogens. Critical requirements for rapid detection methods to support effective and fast management decisions at production lots include time of analysis (within hours), sensitivity and specificity, and validation in real complex samples (Eijkelkamp, Aarts, and van der Fels-Klerx 2009). Pathogen separation and concentration must effectively separate pathogens from sample particulates, remove inhibitory compounds associated with the matrix, and provide sample size reduction with recovery of virtually all pathogens, preferably without disrupting bacterial cell viability (Ruban, Sharada, and Banday 2011; Zhang et al. 2018).

VoC – poultry farm and processing operators. Poultry farmers and processing operators express that due to food safety regulations, poultry processing industries test daily for *Salmonella* species. It is expensive and time-consuming as samples are sent to an offsite laboratory facility miles away. Being able to detect bacterial pathogens within minutes or hours would significantly increase their reaction time both on the farms and in processing plants, allowing them to make immediate adjustments, as necessary. Having the possibility to intervene during the same day or even the same shift saves time and money and improves production efficiency. Access to immediate testing results lowers the risk to their product and would help them better monitor their process in real-time instead of trying to look back and speculating what may have happened. Making real-time decisions due to access to rapid results would enhance decision-making for process improvements and provide helpful information to avoid problems that could potentially put their products and consumers at risk.

TRL 2: Solution or Approach Formulation

Technical gap. There is a technological gap for simultaneous extraction, concentration, purification, and detection of pathogens in field settings close to the contamination site.

Proposed solution. Smartphone-enabled nanotechnology-based pathogen extraction and detection will satisfy the customer's need for a rapid, affordable, accessible, scalable, and simple onsite pathogen monitoring system.

VoC – microbiologists in poultry facilities. Customers express that pathogen tests must be cost-effective, less costly than what they are paying now (USD 50–100 per test), and not have to send their samples to an offsite laboratory; that is, they want to use the technology onsite.

TRL 3: Proof-of-Concept Feasibility

Overview of the biosensor technology. The proposed biosensor combines microbial enrichment, biosensing assay, and smartphone-based data analytics designed to empower proactive and adequate decision-making in food safety. Glycan-coated magnetic nanoparticles (MNPs) are used to enrich the microbial contaminants in the sample, while thiolated gold nanoparticles (GNPs) are used to detect and confirm the presence of pathogens in the sample. The biosensor can be conducted at a higher frequency due to its simplicity, speed, and affordability.

Although MNPs lack specificity to pathogens, they have shown the capacity to extract and concentrate multiple bacteria, increasing the sensitivity of the DNA-based detection assay. The glycan-coated MNPs facilitate the microbial enrichment step. The MNPs can bind to pathogens, and their magnetic nature allows for rapid isolation. This method utilizes only a simple magnet, resulting in easy, rapid, and effective separation. Figure 3 shows the MNPs in solution (left) and a transmission electron microscope (TEM) image (right). Figure 4 illustrates the concept of the magnetic capture, isolation, and concentration of the bacteria from the matrix using the MNPs and how the MNP-cell complexes are displayed on the tube after magnetic isolation through a matting pattern. It shows the matting patterns without bacteria (top) and with bacteria from the sample (bottom).

The thiolated GNPs facilitate the diagnostic test for detecting the DNA of target pathogens. Surface-thiolated GNPs are used as visual color-change reporters. The GNPs demonstrate localized surface plasmon resonance (LSPR) where their optical properties are size-dependent. The LSPR wavelength is sensitive to the surrounding refractive index. The LSPR occurs at visible wavelengths, and for GNPs with a size of 20–30 nm, the wavelength absorption peak is around 520 nm (red color) (Figure 5). In solution, the GNPs are stabilized by electrostatic repulsion, and their red color is maintained. But upon adding an acid, the particles get protonated, destabilized, and aggregated and increase in size. Protonation leads to the coupling of interparticle surface plasmons causing the absorption wavelength to shift to the right and the color to change from red to blue (Jans and Huo 2012; Kim et al. 2008; Zhao, Brook, and Li 2008). The thiolated GNPs are functionalized in the biosensing platform with aminated oligonucleotide probe that is specific to the target bacterial DNA. When the target DNA hybridizes to the GNP-probe, the GNP-probe-DNA complex is formed. The presence of hybridized target DNA protects the GNPs from acid protonation, keeping the color of the solution red, thus resulting in a plasmonic/colorimetric label-free detection. Figure 5 shows the GNPs in solution (inset) and a TEM image, where the GNP size is 20–30 nm. Figure 6 illustrates the concept of GNP-based DNA detection. A positive sample will show red (left), while a negative sample will show blue (right).

Figure 3. Glycan-coated magnetic nanoparticles in solution (left) and TEM image (right)

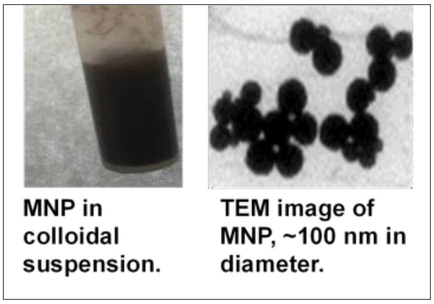


Figure 4. Schematic of the bacterial enrichment: top: no bacteria; bottom: with bacteria

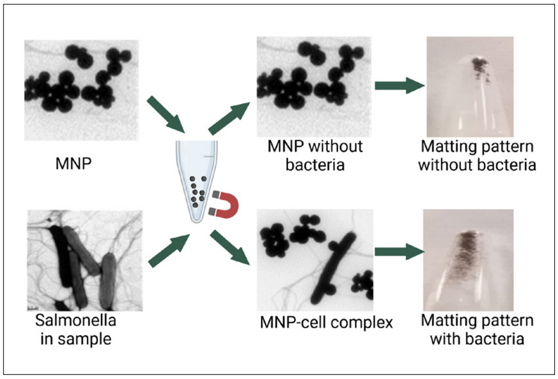


Figure 5. Gold nanoparticles (GNP) in solution (left) and TEM image (right)

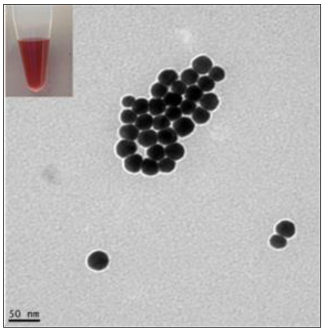
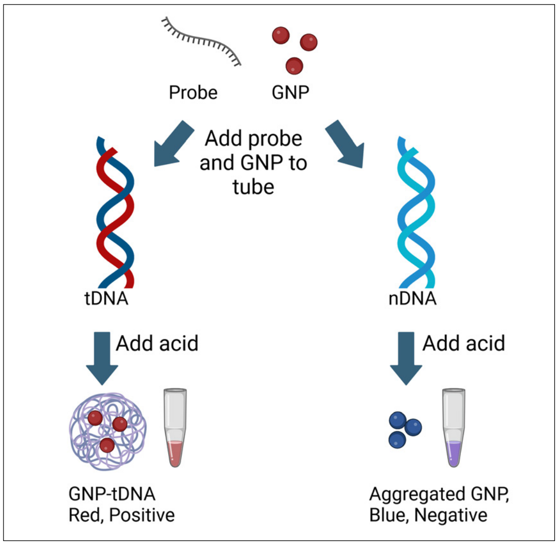


Figure 6. Schematic of the DNA test with target DNA (red) and nontarget DNA (blue)



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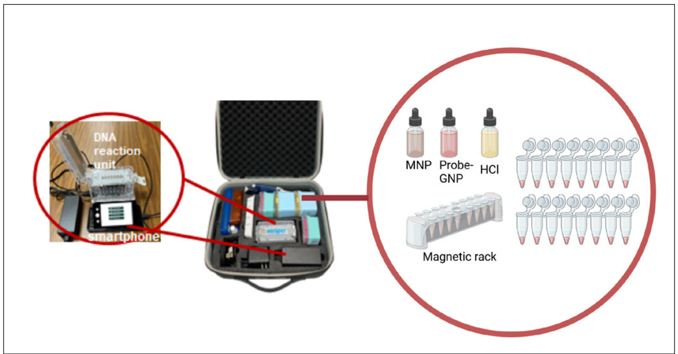
TRL 4-7: Technology Prototyping and Validation Biosensor Prototype

A prototype of the biosensor kit is shown in Figure 7. The biosensor kit includes the biosensor heating device for 16 reactions, reagents, test tubes for magnetic enrichment and detection, a magnetic rack, and a smartphone to operate the device and for data capture and analytics.

Biosensor validation. The MNP enrichment assay takes only 10–20 min, and the DNA detection assay takes only 40 min. The MNPs have been validated to concentrate bacteria from food, environmental, and clinical specimens (Matta and Alocilja 2018; Franco et al. 2019; Gordillo-Marroquín et al. 2018; Briceno et al. 2019; Bhusal et al. 2018). Significant amounts of *Salmonella* Enteritidis, *E. coli*, and *B. cereus* are shown to be concentrated in various types of milk (whole milk, 2%, and fat-free) (Matta and Alocilja 2018). The MNPs can separate pathogens from complex liquids such as homogenized eggs and apple cider (Matta et al. 2018). Once concentrated, the pathogens are detected using rapid biosensor platforms such as plasmonic/colorimetric systems (Dester, Kao, and Alocilja 2022; Boodoo et al. 2023; Caliskan-Aydogan, Sharief, and Alocilja 2023; Yrad, Castañares, and Alocilja 2019; Sharief, Caliskan-Aydogan, and Alocilja 2023), electrochemical systems (Franco et al. 2019; Yrad, Castañares, and Alocilja 2019; Torres-Chavolla and Alocilja 2011; Contreras et al. 2016), and other biosensing platforms (Matta and Alocilja 2018; Franco et al. 2019; Gordillo-Marroquín et al. 2018; Briceno et al. 2019; Bhusal et al. 2018; Yrad, Castañares, and Alocilja 2019; Contreras et al. 2016; Zeeshan et al. 2018). The biosensor has been validated in *Salmonella species*, *E. coli*, *Listeria monocytogenes*, and *Mycobacterium tuberculosis* (Gordillo-Marroquín et al. 2018; Bhusal et al. 2018).

Figure 7. Biosensor kit



Notes: The kit includes the biosensor heating device for 16 reactions, reagents, test tubes for magnetic enrichment and detection, magnetic rack, and smartphone to operate the device and for data capture and analytics.

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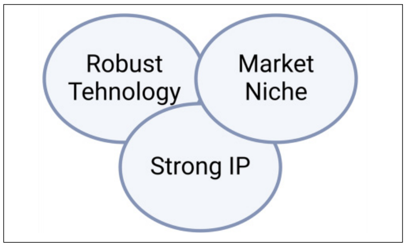
VoC – intellectual property officer, supply chain providers, manufacturers. COTRL 4-7 is the stage to file invention disclosures, apply for patents, and evaluate the protection of copyrights and trademarks. This is also the time to check for the availability of off-the-shelf components of the biosensor kit and manufacture scaled-up technology prototypes.

Three factors affect a successful technology: a well-validated and robust technology, strong intellectual property protection, and a clear market niche and size, as illustrated in Figure 8. Table 3 lists questions to guide in evaluating the technology's robustness, patentability, marketability, manufacturability, and regulatory requirements. Answers to these questions will help in assessing the technology readiness. Eventually, the technology must be produced profitably, and financial investors will seek a robust product, an enforceable IP, and a clear market fit.

Figure 8. Factors influencing a successful customer-oriented and practical technology



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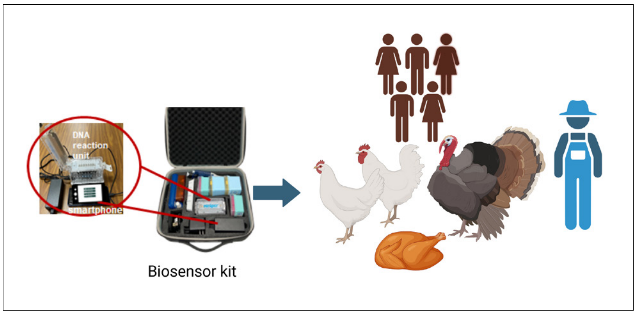
TRL 8-9: System Qualification in Practical Settings

The biosensor is being tested in environmental conditions it is expected to operate to determine if it meets its operational requirements. Figure 9 shows a schematic of the biosensor kit being validated in chicken and turkey farms and meat processing plants. The biosensor is being validated in samples collected from chicken and turkey farms, such as boot swabs, feces, feed, drinking water, and the surrounding environment. The biosensor is also being validated in samples collected from chicken and turkey meat processing plants, such as boot swab samples, cecal samples, carcasses and rinsate samples from rehang, prechill and postchill operations, and samples of component meat products.

Table 3. List of questions that will guide COTRL assessment

Factors	Guide Questions
Robustness	1. Is the technology robust, reproducible, reliable, and valid? 2. Does the technology show high-performance characteristics, such as high sensitivity and specificity? 3. Has enough validation been done to show that the performance criteria, such as sensitivity, specificity, reliability, robustness, validity, and other diagnostic parameters, are excellent and well-established?
Patentability	1. Novelty: What is new about the technology not seen before? 2. Uniqueness or non-obvious: What is unique about the technology not known already? 3. Usefulness: Will someone want to use it? 4. Are there challenges to securing the IP, such as invention not patentable or not protectable, the existence of a dominant IP held by others, the lack of freedom to operate, and the patent not being enforceable?
Marketability	1. Is there a market potential? 2. What are the competing technologies? 3. How big is the potential market share? 4. Is the return on investment high enough for someone to invest in the commercialization effort? 5. Who will be the customers? 6. Why would the customers buy this over the other technologies?
Manufacturability	1. What are the requirements for manufacturing the technology? 2. How much financial investment is required to make this work? 3. Is the production cost low enough that profit can be attained? 4. Who will license the technology? 5. What upcoming technologies would provide the same or even better service or result? 6. Since manufacturing takes time, will the investment not become obsolete before a new competing technology is in the market?
Regulatory Requirements	1. What are the regulatory requirements for the technology to overcome? 2. Can they be addressed within a reasonable time?

Figure 9. Schematic of the biosensor validated in samples from chicken farms, turkey farms, and meat processing plants



Note: Created in BioRender.com

CONCLUSION

A novel COTRL has been presented, a tool that can be used to re-engineer agricultural innovation in SEA. It can be used to systematically assess new agricultural technologies with customer input at every stage of development, ensuring that the early design of the basic scientific research already has the end-products in mind. It is a tool to integrate research, prototyping, and commercialization efforts and facilitate a disciplined and impactful innovation process. The case illustrates how COTRL can assess a diagnostic technology for food safety and public health, ensuring food and nutritional sustainability for the growing global population. For the ASEAN community, the COTRL framework can be a collaborative platform to enable technology transfer and commercialization and connect all sectors to codesign practical solutions for the benefit of member states and the SEA region. It can be used to strengthen the collaboration among academia, research institutions, networks of excellence, and the private sector to create an effective ecosystem for manpower and structural capability development, knowledge sharing, and business development within and across ASEAN nations. The COTRL methodology is an excellent guide to researchers, scientists, research coordinators, funding agency program managers, policymakers, and science and technology facilitators in advancing practical and impactful innovations in AFS in SEA and the world.

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