



BIOASSEMBLER

Integrating bio-inspired assembly
into semiconductor manufacturing
technology for biosensors

Report: Socioeconomic Impact of Multiplexed Biosensors

Version: V6.0

Status: Final

Date: 24 July 2025

Project Coordinator: VTT (FIN)

Project Start Date: 1st September 2022

Project Duration: 36 months

Deliverable N°: D6.5

Dissemination level: Public

Authors: Kristen Connor, Joana Sousa,
Filipe Santos, Gustavo García-López

Contact Person:

Kristen Connor

+351 239 855 570 ext. 110

kristenconnor@ces.uc.pt

info@bioassembler.eu



**Funded by
the European Union**

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101070589. This document reflects the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein

Revision History

Version	Status	Date	Contributor / Partner	Summary of Changes
1.0	Draft 1	13.06.2025	Kristen Connor; Joana Sousa; Filipe Santos; Gustavo García-López/CES	Drafting Report
2.0	Draft 2	18.06.2025	Bernardo Valente; Rita Campos/CES	Review and comments
3.0	Draft 3	14.07.2025	Kristen Connor/CES	Review and integration
4.0	Draft 5	18.07.2025	Filipe Santos/CES	Review and comments
5.0	Final version	22.07.2025	Kristen Connor/CES	Incorporating line edits. Finalization of report
6.0	Final version	22.07.2025	Rita Campos/CES	Review and editing

Contact info

Project Coordinator: Petri Saviranta, VTT, Finland.

Testing, Validation & Data analysis Coordinator: Sami Lähteenmäki, VTT, Finland.

E-mail: info@bioassembler.eu

List of contents

Introduction	4
Key Findings.....	6
Literature Review	9
Case Studies: Forensic Science and Environmental & Food Monitoring	13
Methodology	15
Biosensors and Forensic Science in Portugal	18
Biosensors for Environmental and Food Safety Monitoring	22
Discussion.....	33
Conclusion	37
Sources.....	39

Introduction

Biosensing is a fast-evolving, heterogenous, interdisciplinary, and international area of research and innovation concerned with the integration of biological recognition elements into analytical devices capable of detecting physical, chemical, or biological changes. While micro-electro-mechanical systems (MEMS) sensors such as those used in smartphones, vehicles, and a wide range of Internet-of-Things (IoT) devices have become commonplace, biosensors remain a comparatively specialized technology and have not yet been commercialized to the extent of MEMS sensors. This is due to the technical complexities involved in working with biological materials, strict regulatory environments (especially in health and medical contexts), and the fragmented pathways from research to market (Cagnani et al., 2023; Luong et al., 2008). Despite these challenges, the biosensor industry continues to grow, with increasing interest in expanding its applications beyond healthcare to sectors such as environmental monitoring, food safety, and forensics science, among others. As Singh and Singh (2025) point out, one reason for the continued market growth in this area has been the expansion of biosensing applications outside of the healthcare industry.

This report offers an analysis of the current and future needs for biosensors in two areas of interest: forensic science and environmental monitoring in relation to food safety. Drawing on semi-structured and unstructured interviews and multi-sited participant observation with researchers and engineers across Europe but especially in Portugal, it considers the speculative potential and grounded limitations of biosensors in these domains. We have taken as our goal the exploration of how biosensors are being imagined, designed, and evaluated in real-world contexts. Ample are the studies that delineate potential applications for biosensors and demonstrate proof-of-concept. Less common are studies that attempt to consider what these biosensor applications might look like from a socioeconomic perspective, one that asks about the impact of speculative and emergent biosensor technologies on social, economic, and power relations. In other words, how might biosensors, enrolled as new mediating devices in forensics and environmental monitoring/food safety, transform both economic and social relationships? Our approach to technology is one that is rooted in the history of science and technology, and which shows time and again the entanglement of technology and politics (Edwards & Hecht, 2010), the ways in which diverse sets of actors use technologies to enact and contest political goals (Park, 2024; Mager & Katzenbach, 2021), and wherein technologies can have centralizing or decentralizing tendencies (Goldhaber, 1980; Bloomfield & Coombs, 1992) that are not predetermined but contingent (Verbeek, 2016; Cressman, 2020; de Boer, 2020).

Overview of Findings

Research, innovation, and investment in biosensing technology is rapidly outpacing public awareness of these transformations, or the mechanics (and biology) of the technology itself. This may present challenges to the commercialization of biosensors outside of niche industries and applications. In forensic science, a field broadly open to innovation and the integration of new technologies and approaches, the European Network of Forensic Science Institutes (ENFSI) is an essential clearing house for new technologies. This is especially the case if they are to be enrolled as part of evidence-making

processes and procedures. For biosensors to be widely adopted in forensic science at the national level, the acceptance and approval of such diagnostic tools by ENFSI is an important first step. In Portugal, crime scene technicians also expressed an interest in using point-of-need biosensors to ensure their own safety, for example for the rapid detection of hazards and toxins such as fentanyl or biohazards upon arrival at a crime scene. Meanwhile, environmental monitoring with biosensors is a priority in relation to ensuring the safety, quality, and origin of food. Applications identified in Portugal include the use of biosensors for bivalve monitoring, the management of Recirculated Aquaculture Systems (RAS), fish species identification, fraud detection in seafood and honey, and the development of “smart” food packaging. Investments in biosensing technologies and generalized discourse surrounding biosensors and their potential prioritize the “scalability” of technology over and above the investment in or “scalability” of human workers, creating a contradictory and potentially dangerous disconnect between supposed technological “advancements” and their practical implementation. Effective biosensor design should include grassroots producers and workers to ensure that biosensors build on pre-existing knowledge rather than excluding certain kinds of knowledge and knowers at the expense of exclusionary bureaucracies and large industry players who, at present, stand to benefit the most from these mediatory devices.

Broadly speaking, the dominant model of biosensor innovation positions civil society actors primarily as end-users or consumers of technological products, rather than as co-creators who can and will shape the trajectories of new technologies, whether invited to participate or not. While efforts are underway to transform this outlook, seen through a renewed interest in “citizen science” and “living laboratories” (e.g ECSA, 2015; Leminen & Westerlund, 2019) this framing nonetheless remains among many researchers and engineers who view the social and the political as outside their scientific or technical domain. A key risk identified here is that of reinforcing technocratic models of innovation and governance that prioritize commercialization and control over democratic participation and knowledge-making. At the same time, biosensing with biosensor devices remains an emergent area whose future uses, meanings, and markets are not yet fixed. This openness offers opportunities for participatory models of technological and social transformation that engage civil society in meaningful ways.

Report Structure

The report begins with an overview of key findings, followed by terminologies and definitions, and a review of social science and humanities scholarship related to biosensing. The two case studies and method are then presented, followed by the findings. A final discussion section reflects upon emergent themes, dilemmas, questions, politics, and logics that are at the heart of contemporary biosensor research and innovation. The report concludes with reflections on how biosensors might be more equitably and meaningfully developed and made available in ways that take into account power relations, economic asymmetries, epistemic plurality, and differentiated livelihoods.

Key Findings

Overview of Key Findings

- Biosensor research and investment is outpacing public familiarity with biosensor devices.
- Acceptance of new technologies by the European Network of Forensic Science Institutes (ENFSI) is an essential step for the integration and use of biosensors in evidence-making processes at the national level.
- In Portugal, crime scene technicians express an interest in point-of-need biosensors for occupational safety purposes.
- Environmental monitoring with biosensors is a priority primarily in relation to ensuring the safety, quality, and origin of food.
- In Portugal, environmental monitoring applications for food safety identified in aquaculture, including: bivalve control; monitoring of Recirculated Aquaculture Systems (RAS); fish species identification; food fraud auditing (e.g., seafood and honey); and “active” or “smart” food packaging.
- Investment in biosensing technologies organized around a logic that views technology, but not people, as “scalable” are leading to continued investment and enthusiasm in technology over human-centered innovation.
- Risk of biosensors being enrolled by powerful state and market actors to the exclusion and detriment of small-scale producers and workers.
- Biosensors must be available and accessible to people at the grassroots level so that the technology may build on (rather than replace or exclude) knowledge.
- In both forensics and environmental monitoring for the food industry, biosensor design must take into account the needs and knowledge of grassroots producers and workers.
- Drive for miniaturization an engineering solution to the industrial problem of reducing per-unit production costs to enable expanded scales of production and profit.
- Engineers and scientists deeply motivated by affective dimensions of scientific research, suggesting ongoing need to support “basic” or “fundamental” research in addition to “applied” science and technology.
- Easy-to-use and easy-to-manufacture biosensors may hold potential for expansion of participatory science, environmental monitoring, and knowledge-making at the grassroots level in unpredictable ways.
- Risk of biosensors being deployed by institutions of policing, surveillance, and control against vulnerable or marginalized publics, producers, and actors.

Terms and Definitions

Defining Sensors and Biosensors

As a fast-evolving area of research and innovation, it is important to clarify the terminology used in this report. For those immersed in the world of biosensing and nano-biotechnology, terms like sensor, biosensor, and multiplexed (alt. multiplex) biosensor may seem self-evident. Yet, these terms are often interpreted differently by researchers, engineers, entrepreneurs, users, and the public, depending on disciplinary or educational background, research interest, and orientations to market, technology, and politics. There are also many people for whom “biosensors” as an object category evokes little or no meaning (Campos & Brito, 2024).

Sensors are typically defined as devices that respond to physical stimuli such as light or heat, which then generate a signal that can be interpreted. They are now embedded into many aspects of contemporary life, including smartphones, machinery, and vehicles of all kinds. Nearly 40 years ago, Turner et al. (1987) defined a biosensor as “...a device incorporating a biological sensing element either intimately connected to or integrated within a transducer” (p. v). Today, this “intimacy” can take many forms, as there are a wide range of biological sensing elements and transducers that engineers can select to construct a biosensor. These include enzymes, antibodies, cells, tissues, nucleic acids and other bio-inspired compounds. Transducers, meanwhile, can be electronic, acoustic, optical, amperometric, potentiometric, and more.

With so many possible combinations of biosensing element and transducer, a wide spectrum of devices now fall under this definition of a biosensor. These range from simple lateral flow assays like SARS-CoV-2 antigen and pregnancy tests to more complex continuous monitoring technologies like Continuous Glucose Monitors (CGM). Even within expert communities, these classifications and definitions are up for debate. For example, according to an early-career chemical engineer, the first “real” biosensor was the CGM (personal communication, May 21, 2025). When asked for a reason, they explained that this was due to the CGM’s capacity for continuous measurement in real-time (or very, very close to it). This definition was echoed by other, early career physicists (**Interviewees 17 and 18**). By contrast, more experienced researchers and historians often point to Leland Clark’s 1956 paper on oxygen electrodes as the first biosensor (Newman & Turner, 2007).

The possibilities of continuous monitoring has been a desirable feature of biosensors for nearly 40 years (Turner et al., 1987). Yet, the contemporary emphasis on continuous monitoring as central to the definition of the category suggests that *time* itself has become one of the key metrics of biosensors’ value and function. Continuous monitoring and the ability to generate actionable feedback loops manually or via automation are two salient features of state-of-the-art biosensors as they are being conceived and prototyped today. There is an expectation and a potential, even a promise, that biosensors can and will alter our relations with time, our bodies, and our ecologies. As this report will attempt to show, this introduces new possibilities at the same time that it presents new challenges.

Materials and Geopolitics

As one interviewee explained to our team, “...biosensors, they can be cheap, they can be minimalist, and they can be very sophisticated, and they can be expensive” (**Interviewee 10**). They were attempting to impart on us insight into the wide range of materials, methods, and machinery involved in biosensor fabrication. Indeed, biosensors can be low-cost or “minimalist,” using paper or bamboo substrates and enzymes as the biological recognition element. More complex biosensors—including multiplexed biosensors capable of detecting multiple targets simultaneously—often require chip-based substrates and cleanroom manufacturing processes. This renders the manufacturing of these types of biosensors significantly more capital - and resource - intensive than minimalist or low-cost biosensors.

Energy-intensive, chip-based biosensors are more likely to be developed in the Global North, whereas affordable, paper-based, low-energy alternatives are increasingly emerging from research groups in the Global South. Many labs and researchers situated in the Global South do not have access to the research funds or facilities that would allow them to order expensive biological elements, or access the machinery or cleanroom facilities to build chip-based biosensors, although there are exceptions. These divergent geographies of research and innovation underscore that biosensor production and manufacturing, much like biosensor consumption, is structured by geographical inequalities. This uneven terrain is further reflected in publication patterns that are currently dominated by organizations and researchers based in China, the U.S., and Europe (Valente et al., 2024). Geography not only influences the type of biosensors that are in development and publication patterns, but also the imaginaries of how they should be used, by whom, and to what ends.

What is Biosensing?

As with *biosensors*, definitions of biosensing vary according to actor and context. Among biosensor builders, biosensing typically refers to the detection or quantification of a substance through the use of a biosensor in the Turnerian sense (Turner et al., 1987). More recently, anthropologist Dawn Nafus (2016) offered a definition of *biosensing* to refer, “...to any practice that uses information technology to understand something about bodies or the environments in which they live, whether the technology is cutting edge or not” (p. xiv). In this broader definition, it is the use of *information technology* that distinguishes *biosensing* from various other historical and contemporary forms of mediated sensing.

The mediation of human sensing is not new: across time and place, people have sought to enhance their limited sensory capacities by forming relationships with non-humans, including animals, plants, tools, and technology. Guide dogs, honeybirds, pigeons, and bees are among the many creatures that communities have sought to forge intimate relationships to enhance their perceptive capacities. Meanwhile, something as seemingly common as a mirror stands out as an ancient sensory device, one that has altered peoples’ sense of self, others, and the places around them.

Viewed in this way, there is nothing new about using technology and relationship to other beings to better understand our bodies and environments. What *is* new is the expected integration of

biosensors into expanding digital infrastructures and data economies, and the multiple, unpredictable ways in which they might reshape how bodies and ecologies are conceptualized, analysed, understood, managed, and governed. Given the existing geopolitical inequalities in biosensor research, design, and knowledge production, it is essential to both draw and pay attention to *whose* biosensor visions and designs receive investment and support, to what ends, and to the exclusion of whom or what alternatives. In sum, although the broader definition of biosensors (Nafus, 2016) better reflects popular understandings of biosensing, for the purposes of the narrow scope and focus of this report we adopt Turner's et al. (1987) definition of a biosensor.

Literature Review

Biosensors in the Social Sciences and Humanities

Neither biosensors nor biosensing are subjects around which a cohesive scholarly conversation is organized in the social sciences and humanities. One reason for this is that scholarship on the sociology, history, and philosophy of science, as well as science and technology studies (STS) deal with many of the questions raised by biosensors and their makers. This will likely change in the near future, but to date there is one edited volume, *Quantified: Biosensing Technologies in Everyday Life* (Nafus et al., 2016), that grapples with biosensing from a social scientific and humanistic perspective. Contributions to *Quantified* (2016) reflect many of the dominant themes that have shaped the field of STS over the past 40 years, including theorizations of the technology through the framework of biopower and biopolitics (Kragh-Furbo et al., 2016); datafication, self-surveillance, and the quantified self (Sherman, 2016; Wolf, 2016); Big Data, privacy, and "data citizenship" (Taylor, 2016; Nissenbaum & Patterson, 2016; Gregory & Bowker, 2016); and personhood, the body, and the "dividual" (Strathern, 1988; Day & Lury, 2016). The central contribution of this volume lies in its theorization of biosensors as key mediating technologies that have been enrolled in uncertain, often complex relationships between medical practitioners and patients; people and their sense of self; expert science and everyday understandings; and community and commercial interests. This focus on the mediatory role of biosensors has informed our central research question and approach.

Technologies of Humility and Hubris

Over the course of this research, our team was only able to see and interact with one biosensor prototype. This posed a unique challenge as we were unable to study biosensors, their users, or their makers *in practice*, using or building these devices in every-day settings. One reason for this is the current stage of biosensor devices for non-health applications. All of the applications mentioned in this report are in the prototype stage, and therefore not yet available on the market. Methodologically, this posed challenges which will be discussed in more detail in the Methods section. Analytically, the uncertainty around biosensing technologies, and our own uncertainties in relation to the object category drew us to Jasanoff's (2007) paper, "Technologies of Humility." She asks: why have "we" (moderns; *Nature*-readers) become so uncomfortable with uncertainty? In other words, why do we believe *certainly* is an attainable state? Jasanoff contends that the contemporary focus on

definitive answers results from “the spread of binary thinking that frames the future in terms of determinate choices between knowledge options.” For her, digital logics are built into our computers, mobile phones, and “...dominate the framing of social problems and options for dealing with them” (p. 33). Biosensors fit comfortably in this framing, even as we know from experience and empirical engagement that life rarely unfolds into binaries, and there is no reason to assume that the interaction and interface between people and biosensors would be any different.

Although the field of biosensing has been around for some decades now, biosensor technologies remain an emergent domain. Emergent in the sense that biosensors develop in unpredictable and nonlinear ways, evolving through a mixture of scientific innovation, regulatory shifts, societal needs, and ethical contention. The COVID-19 pandemic cast this emergent quality into sharp relief when national emergencies and global uncertainties created the conditions for the accelerated investment, development, authorization, and release of biosensors. Analytic tools like the Rapid Antigen Tests (RATs) that had been under development but not yet commercialized were suddenly among the most ubiquitous tests and household items (and waste) around the world (Morales-Narváez & Dincer 2020; Paunov & Planes-Satorra, 2020). Currently, the post-pandemic moment is marked by heightened enthusiasm for and investment in biosensors. However, our research suggests that this investment and innovation is outpacing public, everyday familiarity with these devices, especially in the area of non-health biosensors. There are expectations of high demand from within the biosensor’s scientific community, but case studies from Portugal suggest that this demand is not matched by a public appetite or interest for these kinds of devices for non-medical applications.

Rather than treating uncertainty as a problem to eliminate, we have adopted it as a lens to understand how biosensors might transform forensic sciences and food quality monitoring in Portugal. Embracing uncertainty demands epistemic humility, an acknowledgement that no single discipline, model, or method can fully grasp the societal implications or ethical complexities of biosensor technologies. With this stance, we have sought to ask: What purposes do biosensors serve? Who might be harmed by their deployment? Who stands to benefit? How do we know what we claim to know about biosensors and their relation to society? The greater the uncertainty in response to these and other questions, the more humility is warranted in our approaches to innovation, governance, and public engagement.

The inverse of *technologies of humility* are *technologies of hubris*, an approach to science and innovation that prioritizes speed, expert authority, market potential, control, predictability, and technical solutions (Jasanoff, 2007). These keywords are at the core of biosensor innovation speech, most commonly reflected in those presentations and pitches required for scientific researchers and engineers to attract funding to support their work. As an approach, *hubris* assumes expert knowledge and technologies alone can manage societal risks and progress, often marginalizing ethical concerns, alternative perspectives, and public engagement. By contrast, a humble approach proposes that scientific knowledge has limitations; uncertainty, ignorance and indeterminacy are always present; technologies have unforeseen consequences; experts do not have control of outcomes; and that we must examine the distribution of risks alongside questions of equity, justice, and environmental

justice. Just because a technology *can* be developed, *should* it? In the contest of this project, humility guides us through the ambiguities, complexities, and indeterminacies in the current state of biosensor applications.

Expectations, “Future-Oriented” Abstractions, and Tech-Solutionism

Given the limitations which prevented us from studying biosensors *in situ*, interviews emerged as the primary method for understanding biosensors and biosensing. Across all interviews, expectations emerged as a key theme, especially expectations that a given biosensor will play a specific role in solving a current or future world problem. Borup et al. (2006) described such expectations as “future-oriented abstractions,” that are generative in that they produce outcomes. They shape actions, establish frameworks, provide legitimacy to projects, draw attention, encourage investment, and offer a sense of direction and purpose. Expectations both act upon and construct the present. We can look to the green energy transition for a contemporary example of the impact of expectations. Currently, many people envision renewable energy technologies to be the solution to the climate crisis. Consequently, institutions and states enact policies, legislation, and subsidies to pursue this expectation, when there are a multitude of other possible, lower-tech approaches and alternatives. For a historical example, we might consider the Green Revolution, and the countless programs organized globally to “feed the world” through the modernization of agriculture. These programs did not achieve that goal. Instead, they oversaw the expansion of agrochemical and seed markets, the privatization of land, and land-grabbing from peasant and small-scale farming societies (Basu & Klepek, 2015; Patel, 2013).

Although expectations have long played a role in shaping science and technology, their impact has increased over time. Exaggerated hopes for future breakthroughs have become especially prominent in the context of late modern industrial society (Borup et al., 2006). In the current moment, marked by technological solutionism and optimism, technological expectations such as those surrounding biosensors and, even more dramatically, artificial intelligence, are uniquely able to mobilize resources, influence decisions, and create new realities to the exclusion of alternatives that may be more democratic, affordable, and environmentally sustainable. Expectations are not predictions: they actively shape the present by directing resources to what are understood as good opportunities or investments. This matters because such expectation-drive outlooks risk overlooking simple means, tools, and approaches that are already at hand to solve dilemmas, confront injustice, and build more equitable futures.

Unbounded Risk

Tech-solutionism and optimism, increasingly understood as forms of “rational superstition” (Wilson, 2017) or “unacknowledged mysticism” (Stahl, 2009), are widely associated with positive and beneficial traits supposed to be inherent in innovation (Soete et al., 2010). Risk society theory, by contrast, acknowledges that innovation can produce both positive and negative consequences (Gonçalves, 2012). Beck (2002) argues that in our contemporary “risk society,” the spatial, temporal, and social boundaries of risk have become un-bound. In other words, whereas risk may previously have affected a bounded or circumscribed area or population, globalization and attendant transformations mean

that risks are more likely to affect wider areas or populations. Examples of axes of conflict in a world risk society include ecological conflicts, global financial crises, and the threat of global terrorism. It is not the case, Beck asserts, that life has become more dangerous, but that uncontrollable risks have become de-bounded (Beck, 2002, p. 41). Because risk is itself a modern concept, which presumes that a given danger has an actuarial or probability-based calculation that can be inferred and controlled.

Over two decades later, we can fully notice the author's foresight into the future areas of conflict and how, as predicted, the consequences and effects of the multiple crises are global but unequally distributed. Therefore, when uncontrollable risks become unbound by frontiers, a global consciousness should arise so that global solutions must be found. In this century alone, we have witnessed several environmental catastrophes, global financial crises, and the justification of transborder terrorism to several invasions, wars, and the ever-expanding global surveillance assemblages. More recently, the COVID-19 global pandemic epitomized the features of the global risk society. Innovation processes should consider the de-bounded aspects of risk, not only in terms of territorial and temporal dimensions, but also in its social impacts, which tend to be unequally distributed, like the knowledge and resources to mitigate them.

Post-Normal Science and Humility

The idea of post-normal science (PNS) contributes to our team's framework to think through technological innovations and interventions from the perspective of humility rather than hubris, and adds an emphasis on a more democratized and inclusive scientific process. PNS is a problem-solving strategy proposed for situations when there are uncertain facts and high complexity, multiple legitimate perspectives and disputed values, high stakes and urgency of decisions (Funtowicz & Ravetz, 1993; also, Saltelli, 2024). In other words, it is a science for so-called "wicked problems," which are problems that are unique, novel and very difficult to solve, a characteristic of most if not all environmental problems today. Kønig et al. (2017) review the PNS literature and sum up its ethos (norms and values) as Transparency, Robustness, Uncertainty, Sustainability and Transdisciplinary (TRUST). This approach emerges with concern for improving the social robustness of science – particularly in its applied and policy-oriented forms (Haklay et al., 2023).

Quality and not knowledge is the main goal; it is not only about the "product" or outcome of the scientific process, but also about the process, people, and purposes where knowledge needs to be imputed into decision-making for sustainability (Funtowicz & Ravetz, 1993). Embracing uncertainty, adaptability, flexibility, creativity and precaution are key elements of this robustness. Saltelli (2024) for her part identifies three "simple keys" of PNS: reflexivity, the non-separation of values and facts, and an "extended community of peers." Reflexivity refers to scientists' critical self-reflection about the scientific process as embedded in societal dynamics, and the application of social theories to the research itself. The extended peer community refers to going beyond a single discipline (including multidisciplinary groups of 'experts') and beyond 'experts' (including so-called 'lay' actors with a stake in the issue) to engage in a deliberative dialogue. In this sense, there is a strong connection between PNS and citizen science (Haklay et al., 2023), as well as with transdisciplinarity.

Finally, because of its questioning of traditional scientific ‘expertise’ and its recognition that it is neither value-free nor ethically neutral, PNS has also been described as an “uncomfortable science” and a “humble science” (Saltelli, 2024). Humility is promoted by awareness and reflexivity about the limits of science for prediction and control, and guides science towards adaptability and democratization (Kønig et al., 2017). It is with these perspectives in mind that we approached the two case studies, introduced below, to examine biosensors for forensic science and environmental monitoring/food safety in Portugal.

Case Studies: Forensic Science and Environmental & Food Monitoring

Case Study 1: Biosensors and Forensic Science

Forensic science, also sometimes called criminalistics, is a field in which scientific methods are used to examine evidence and investigate crimes. A fundamental goal of forensic science is to examine and present evidence that can be used in court. To achieve this goal, forensic scientists and technicians must use reliable methods, standardized procedures, and validated tests. An interdisciplinary field, forensic science can include methods and approaches as wide-ranging as DNA and fingerprint analysis, photography, pathology, toxicology, and many more. Given that global biosensor research and investment prioritizes innovation for healthcare and medical diagnostics industries, the question of biosensor applications, risks, and benefits in forensic science is an important one. If biosensors can help people monitor their health in life, what are the use-cases of biosensors, for example, in post-mortem cases, or cases involving potentially dangerous or toxic substances? More specifically, what are the demands, possibilities, and limitations of multiplexed biosensors in forensics?

There is an expectation among promoters and builders of biosensors that they could have a substantial impact on forensic science in the coming years, despite forensics not being a major focus area for biosensor research and innovation currently (Yáñez-Sedeño et al., 2019). A scan of presentations in a recent biosensor conference reveals the extent to which the body, and its many substances, are imagined as an almost infinite horizon for analysis and data harvesting. From saliva and breath, to tears, blood, urine, sweat, sperm, quantitative and qualitative biosensors are currently being designed for the analysis of each of these fluids and more. Forensic scientists and crime scene technicians encounter a range of other substances in their work, many of which are potentially dangerous including fentanyl, arsenic, cyanide, among others, whose early detection could protect crime scene workers and potentially aid investigations. The unique features of biosensors that are expected to be applicable to forensics are the ability of these tools to detect miniscule traces of substances, their affordability, and ease of use (Yáñez-Sedeño et al., 2014). Discussions of the applicability of biosensors to forensic science, however, are often approached from the perspective of the laboratory, specifically a deep understanding of the technology and its analytic potential, despite many applications being at the proof-of-concept stage (Yáñez-Sedeño et al., 2019; Celikbas et al., 2019; McGoldrick & Halámek, 2020). The approach adopted in this study, by contrast, is ethnographic, namely, understanding the

hypothetical applications and uses of biosensors from the perspective of crime scene technicians, contextualized within the institutional and evidence-making structures of the Portuguese police, courts, and associated laboratories.

Case Study 2: Biosensors for Environmental Monitoring and Food Safety

The second case study began with the aim of exploring the applications, needs, risks, and challenges of biosensors for environmental monitoring in Portugal. As discussed in the Methods section below, our research continually pointed to other priorities, specifically related to food safety. Interviews and discussions with researchers based at public research centres with a focus on the study of the environment brought us to projects and consortia developing biosensors for various kinds of food quality control, often supported by a mix of public and private funding.

Questions of food security, safety, “fraud,” and its corollary, *authenticity*, loom large in biosensor research and innovation, as they do in the food industry more broadly. Take for example the recent World Biosensors Congress held in Lisbon (May 2025), where Professor of Food Security and Diagnostics at Queen’s University, Belfast, Katrina Campbell, gave one of two introductory, plenary speeches, marking the opening of the conference, and signalling key foci in contemporary biosensor research. The other talk focused on what industry insiders refer to as “organ-on-a-chip” (OoC) devices. Campbell emphasized the transformative role that biosensors can play in the global food industry, wherein food is both being produced on an ever-increasing scale and travelling further distances satiating far-away consumers. Increasing quantities of food, stored in multiple kinds of containers, places, and under changing conditions (temperature, humidity) raises enormous problems. Rapid, affordable tests with reproducible results offer the possibility of verifying food at different points in its production and storage, packaging, transit, sale, and consumption (which do not necessarily happen in this order and frequently occur multiple times in the supply chain). Biosensors could be used, to name just a few examples, to detect the presence of high levels of antibiotics in milk and meat; dangerous and deadly toxins and bacteria in seafood and other; pesticides and endocrine disruptors; pathogens and viruses; for the detection of food fraud and ensuring the authenticity of a food item or product (Griesche & Bäumner, 2020; Curulli, 2021; Wang et al., 2022; Pal et al., 2024). In Campbell’s (2025) description, “novice end users” such as farmers, fishermen and women, or citizen scientists need not necessarily know what is in the “cartridge” (the device) or how it works, but that it is reliable and easy to use.

The growing emphasis on food safety, traceability, and authenticity is reflected in biosensor research in Portugal as well. Our study identified projects aiming to tackle issues including neurotoxin detection in bivalves, water quality control in aquaculture, verification of fish species, authentication of honey, and smart packaging that can detect (and signal) food freshness. Findings from both case studies will be discussed in more detail, following a review of the research methodology.

Methodology

Qualitative Approaches

This report draws on a range of qualitative approaches including semi-structured interviews, multi-sited ethnography, and qualitative coding. Our conversations engaged 21 biosensing stakeholders, including researchers, scientists, engineers, and members of the public. We focused on three main domains: interdisciplinary biosensor research and innovation; forensic science; and environmental and food monitoring for safety purposes. Ethnographic work consisted of active participation in the BioAssembler consortium; site visits to the laboratories of consortium partners; attendance and engagement at the leading international biosensors conference; and involvement in inter- and multi-disciplinary initiatives such as the BioAssembler Advanced Training Course. Each of these places and spaces offered moments of conversation with people working on or with biosensors, and many who had never heard of a biosensor.

Round One Interviews: The BioAssembler Team

The first round of interviews consisted of eight individual semi-structured interviews with members of the BioAssembler team, selected for their experience, knowledge of the BioAssembler project and biosensing field, and responsibility for different scientific tasks within the project (fluidics, DNA synthesis and coding, conjugation and assembly, testing and validation). The aims of this exploratory phase of research were to develop a general understanding of the landscape of international biotechnology research and collaboration; to deepen our understanding of biosensor technology and vocabulary; to identify practices of interdisciplinary dialogue in biosensor research; to map the main stages and concerns in the production of biosensors; to establish a basic understanding of state-of-the-art and beyond-state-of-the-art biosensor technologies; and to begin to tease out the internal logics, dominant paradigms, and foundational ideas in this field in order to better understand its visions of itself and of the future. These interviews also provided an opportunity to explore BioAssembler team members' definitions and perceptions of current and future biosensor applications, risks, challenges, and opportunities. Methodologically, they provided an initial data set in the form of recorded and transcribed anonymized interview scripts to begin the process of open or inductive coding (Glaser, 1967; Charmaz, 2006).

Round Two Interviews: Crime Scene Technicians

The second round consisted of one semi-structured group interview with two crime scene technicians in Portugal. Given the specificity of forensic work and the relevance of point-of-need biosensing, the sampling strategy focused on professionals that specialize in crime scene work, including trace detection and collection. There are very few people in Portugal that are trained in this type of crime scene work. We attempted to interview another team in another city, but working in the same institution; however, institutional constraints precluded additional interviews. Nevertheless, given the interviewer's extensive experience in the study of the forensic field; its structure and informational requirements; and articulation with end-users, we drew additional data and insights from previous research and bibliographic sources.

Round Three Interviews: Environmental Monitoring & Food Safety Stakeholders

The third round consisted of 11 semi-structured and unstructured interviews. These included five individual semi-structured interviews, one semi-structured group interview with two individuals, and four unstructured interviews. The majority of these conversations were with scientific researchers based at public institutions at all stages (PhD student, early career, established researchers), some of whom also work as consultants in the private sector. We also spoke with people who work at a fish market in southern Portugal. Some researchers were working directly on developing biosensors, but most were from other fields and had some contact with biosensors as a result of their main area of research. These were among the most varied interviews, in that no two conversations covered the same kind of biosensor or hypothetical application.

Methodological Challenges: Talking about Biosensors

When we first directed our analysis towards the field of environmental monitoring, broadly speaking, we started by contacting the most relevant institutions that regulate people-environment interfaces in Portugal. These included public institutions such as the Agência Portuguesa do Ambiente (APA, Portuguese Environment Agency) and the Instituto para a Conservação da Natureza e Florestas (ICNF, the Institute for the Conservation of Forests and Nature). We also contacted national-level associations working in nature conservation, organic farming, and small-scale farming, such as Quercus, Associação Portuguesa de Agricultura Biológica (AgroBio, the Portuguese Association for Organic Agriculture), and Associação Nacional dos Pequenos e Médios Agricultores (ANPEMA, the National Association of Small and Medium Farmers). These efforts yielded limited engagement. Only two national-level organizations responded to our inquiries, one working in the area of organic agriculture and the other focused on environmental issues. Both mentioned that they had no technician or team member with knowledge of this kind of technology. Since we considered the question of biosensors and environmental monitoring to be an important one, we followed up clarifying that we would be eager to discuss monitoring in general, even absent biosensors, and the one reply we received indicated there was no one available to talk to us.

This lack of reply, as with the difficulties in recruiting more teams working in forensics, raised several initial questions, including: are these organizations already using biosensors? Were our requests to discuss “biosensors” met with a public not familiar with the term? Did our status as social scientists asking about biosensors generate confusion in terms of field, domain, or expertise? Rather than frame this as a setback, we tentatively interpret this lack of response as suggestive of the current status of biosensing within the environmental and forensic science fields in Portugal as one in which awareness, access, and institutional familiarity with these technologies remains limited.

This experience reshaped our interview strategy for the environmental study case. Slowly, we grew more familiar with the biosensing field and understood that although there are countless proposed biosensors for environmental monitoring, few of them have moved beyond the proof-of-concept or prototype stage. Existing literature suggests that in terms of actual use, it is among the military, specifically unmanned aircraft such as drones that use biosensors for “surveillance, reconnaissance, and military missions” (Justino et al., 2017). While there are numerous reviews of biosensors for

environmental monitoring, identifying the many substances that biosensors can be used to detect (e.g., Rodriguez-Mozaz et al., 2005; Justino et al., 2017; Gavrilas et al., 2022; Huang et al., 2023; Williams et al., 2024); our goal was to understand the devices *in situ*, and to understand how biosensors as mediating devices might impact social and economic relationships.

Methodological Shift: From Environmental Monitoring to Food Safety

As a result of these challenges identifying people who had some knowledge and familiarity with biosensors being developed and/or used in Portugal, we turned to university-based researchers, centres, and institutes working with or on biosensing for environmental monitoring. Through these interviews we were able to gain a better insight into biosensing applications, albeit not without another turn in direction. This research pointed directly to food security and food safety as a priority area for biosensing technologies in the Portuguese context. Environmental monitoring is a piece of this, but it is important in this context insofar as environments where food is grown, kept, or animals raised and harvested need to be monitored for bacteria, toxins, viruses, chemical composition, and so forth, for the purpose of ensuring the safety, quality, and origin of *food*, not the health of the environment or a specific ecology as an end unto itself.

All interviews were analysed using grounded theory, beginning with open or inductive coding to allow themes to emerge from the data. As briefly discussed above, first round interviews allowed us to identify key literatures and concepts that would be most useful to us, especially given the focus on imagined, expected, and possible applications, for introduction and use in an unspecified but palpably near future. These codes were then grouped and refined into a hierarchical frame focused on applications, benefits, challenges, and risks of biosensing in these domains. As the dataset grew, the coding frame was iteratively adjusted and interviewed and re-analysed for consistency.

Ethnographic research supplemented the interviews. These included BioAssembler meetings and laboratory visits, which allowed for insight into the collaborative dynamics of the field and shared techno-scientific framings of biosensors within the BioAssembler consortium. We drew additional insights from the World Biosensors Congress, a three-day conference in May 2025 featuring researchers, industry partners, policymakers, sponsors, and corporate stakeholders from around the world. After multiple days of interviews with researchers about biosensors and aquaculture, we visited a coastal fish market to hear the perspectives of fish vendors and market managers. Interactions and engagements ranged from multi-day events and extended interviews to brief, even fleeting conversations that together inform the analysis and findings.

One persistent methodological challenge was our limited access to functioning biosensor prototypes. Over the course of this study, our team encountered only one working device. The elusiveness of material biosensors mirrored the elusiveness of interviews in non-academic and grassroots environmental monitoring settings discussed above. This absence, and the uncertainties they generated and continue to generate, are instructive in that they point to the importance of expectations and speculation to the biosensing field especially for applications outside of the healthcare and medical sectors.

Findings from round two (forensics) interviews will be discussed in detail below, followed by an analysis of round three (environment-food safety) interviews.

Biosensors and Forensic Science in Portugal

The Portuguese case study has potential for extrapolation, meaning that it may be analogous to other European justice systems albeit with some limitations. The application, use, and adoption of biosensors for forensic applications in Portugal is contingent on several factors, including evidence-making structures, epistemic boundaries, and the court system. Although as a field forensic science—including the crime scene technicians interviewed for this study—are generally open to new technologies, all new technologies and methods face their own trials before becoming standardized and accepted (or rejected) by legal communities (Koehler, 1993). As Morgan (2023) has pointed out, in some cases, this can take decades.

Making Acceptable Evidence

As an inquisitorial-type criminal justice system, its structure and institutions tend to rely on a sort of interdependent neutrality or impartiality (Kruse, 2012). The fundamental objective of a criminal inquiry is to find the “truth of the facts.” In Portugal, the Ministério Público (MP, the public prosecution service) is the entity responsible for the coordination of the criminal inquiry, and represents the state in court. The coordination role of the MP involves the use of criminal police agencies to carry out the necessary tasks. As in other European countries, there are different police structures dedicated to different needs. Besides the Polícia de Segurança Pública (PSP, Public Security Police) and the Guarda Nacional Republicana (GNR, National Republican Guard), the Polícia Judiciária (PJ, Judiciary Police) is assigned with the investigation of more severe (e.g., crimes with firearms and crimes against life), and complex crimes (e.g., organized crime, white-collar crimes). Unlike the GNR and PSP, which are under the Ministry of Internal Administration, the PJ operates under the Ministry of Justice, and has its own forensics department, the Laboratório de Polícia Científica (LPC, Laboratory of Scientific Police). The LPC develops forensic expertise in several areas (ballistics, forensic biology, toxicology, physics, chemistry, etc.) primarily for the PJ, but is allowed to cooperate with other entities. The Instituto Nacional de Medicina Legal e Ciências Forenses (INMLCF, National Institute of Legal Medicine and Forensic Sciences) is an autonomous institution under the Ministry of Justice and, under Law 45/2004, all *perícias* are to be carried out by their staff and in their facilities, or by services contracted by them. A capacious concept, *perícias* include any method, technique, technical analysis or exam carried out by experts or specialists in order to answer the questions posed by the courts, police investigation coordinators, or public prosecutors. In sum, all evidence that reaches a Portuguese criminal court is produced by either the LPC or the INMLCF.

Epistemic Boundaries, Trust, and the Courts

As argued by Santos and Costa (2024), the inquisitorial framework of the Portuguese justice system, which has similarities with other continental justice systems, engages in an apparent inter-agency

neutrality. The practical implication is the fostering of particular ways of constructing and interpreting scientific evidence. In this fully impartial setting (Kruse, 2012), forensic experts go to great lengths to avoid making statements that could bear inference on the interpretation of the evidence. The increasing specialization and standardization of practices over the last decades has meant that there are more epistemic walls, professional and knowledge boundaries, along the chain of custody between crime scene technicians (who collect traces), judiciary police (who submit traces to the laboratories and specify the exams that are to be made), the forensic laboratory technicians (that perform the requested analyses and examinations), the prosecutors (who will produce an accusation based on the available evidence), and the judge (who will appreciate the case and, ultimately, has the power to request additional forensic exams).

The institutional semblance of neutrality means that a high degree of inter-agency trust is a requirement for the effectiveness of judicial affairs. Moreover, as stated in Article 163 of the Portuguese Code of Criminal Procedure (2007), technical, scientific, or artistic examinations are not to be subjected to the trial judge's free interpretation. If the judge does not agree with the exam, they must be prepared to justify their decision. This scenario creates an incentive for legal actors to trust forensic science and accept exam conclusions. However, this also contributes to a "rubber stamp" culture, where judges may conform to having the forensic evidence produced during the investigation, which is often irreversible. Since experts avoid interpretation of the evidence in regard to the circumstances of the case, at least in formal terms, it is possible that the contamination or transference events are rarely pondered in court unless challenged by a competent defense lawyer (Santos, 2014).

Standardization, Interoperability, and The European Network of Forensic Science Institutes

The Portuguese forensic science service providers (INMLCF and LPC) are certified by ISO 17025 and the LPC is a member of the European Network of Forensic Science Institutes (ENFSI). ENFSI was created in 1995 following a meeting between representatives of eleven state forensic laboratories from Western European countries to discuss matters of common interest. In 2009, the European Commission granted ENFSI monopoly status for forensic sciences in Europe. ENFSI is the legitimate and authorized institution for all matters regarding forensic sciences, engaging in the development of standards, operating protocols, training, assessment of proficiency, and research in the European Union. With the increasing cross-border cooperation in judicial and forensic matters, it is fundamental that forensic techniques and procedures are mutually compatible and recognized.

In its statement for the "Vision of the European Forensic Science Area 2030," ENFSI defined three areas where it aims to develop its strategic goals (ENFSI, 2021). Besides strengthening the quality in the expression and impact of forensic results, and in demonstrating its reliability, ENFSI's vision for addressing the challenges of the future includes attention to new and emerging developments, not only in applications of AI and nanotechnologies, but also to "emerging biological and chemical evidence types '-omics'" (ENFSI, 2021). This is potentially relevant for biosensing applications. As the document states, these include:

...novel methods of analysis ('-omics') that can lead to the identification of large molecules such as proteins or metabolites which can provide information about people, their activities and their environment. This has already proven their value to forensic science, especially where samples do not contain DNA or its analysis is limited to degradation or interferences, the sample may contain sufficient proteins for informative analysis. ENFSI should keep updated concerning emerging techniques to be aware of their possibilities/limitations, promoting dissemination of knowledge and advancements in this broad area (ENFSI, 2021, p.2).

In short, the acceptance of new techniques and approaches by ENFSI is an important step in the integration of new technologies into national evidence-making systems.

Besides the general definition of forensics as the application of science to address legal questions (Ribaux et al., 2010, pp 10), the pragmatic and overarching purpose of all instruments, exams, and techniques available to state-of-the-art forensic science is mainly concerned with identification. Traditional disciplines of forensic science like dactyloscopy or fingerprinting, tool marks, handwriting analysis, have long laboured on the comparison of observable attributes, and produced claims about tracing a mark to a unique source (Saks & Koehler, 2005; 2008).

The emergence of forensic DNA technologies has played a leading role in the reconfiguration of forensic science practices, standards, and protocols, which is concurrent with the increase in European transnational cooperation in judicial, security, and forensic matters (Santos, 2017). At the present time, there are multiple categories of data being exchanged among EU countries for policing and security purposes, but also for criminal investigation and judicial prosecution. Necessarily, data exchange generates interoperability requirements, which facilitates the demand for standardization and mass production of consumables.

Forensic Science and Technological Optimism

The field of forensic science can be viewed as particularly open and optimistic towards technological solutions that promise to improve workflow and increase turnover times (Quinlan, 2020). Simultaneously, new forensic technologies have brought a degree of certainty, reliability, and scientific robustness that were found to lack in traditional forensic disciplines like ballistics or fingerprints (Murphy, 2006; Saks & Koehler, 2005). Therefore, it is not a field necessarily adverse to innovation, but rather keen on integrating new solutions to its challenges.

For example, for detection of blood in crime scenes, there are several ways to do it if it's not visible to the naked eye. As two interviewees explained:

Interviewee 19: With blood there is a different approach because sometimes blood is visible, we have a stain... a brownish-red stain, it looks like blood, and we check with the test. But it can also be latent blood (...) for example on the upholstery of a car there is a

blood stain that we cannot see, the cloth is dark, and therefore we use luminol which will react with the blood...

Interviewee 20: Or we can also use the infrared camera.

Interviewee 19 - (...) The infrared produces a contrast on a dark surface (...) through different wavelengths (...) the cloth becomes lighter, and the stain becomes dark, so we know that there is something there that might be blood.

Moreover, we inquired into possible applications of biosensors that could provide additional information. Pondering the types of tests and crime scene technologies already available, as well as the potential informational needs in the context of forensic science, we drew an example from the analysis of a criminal case file where the estimated time of death was crucial to establish who committed the crime.

Interviewer: One of the issues where we thought that biosensors could, hypothetically, be useful could be the estimation of the time of death. We would ask you if it could be possible to have some sort of test to measure the degradation of a trace in order to quantify how many hours or days the blood is there?

Interviewee 19: We were just talking about it at lunch, about some blood stains where the court will probably question the date of that blood and we do not have the capabilities to say, we cannot tell how long that blood has been there.

The interviewees provided an example of a potential use for biosensor tools in forensic casework, which is related to environmental monitoring.

Interviewee 20: Imagine if we want to go into an atmosphere contaminated with (...) it would be useful to use some sort of tool, or to test if the atmosphere is contaminated and if we can go in safely (...) because our safety comes first and then the [crime] traces, right? (...) The trace is not worth it [to risk one's life] (...) if we are getting into a place where we don't know if it is contaminated, there are some who talk about aerosols and some drugs that are out there.

Interviewee 19: A clandestine drug lab, for example, we don't know what it holds for us.

Interviewee 20: Fentanyl...

Interviewee 19: Fentanyl, exactly. Fentanyl has some risks, so for us, in terms of safety, it [a biosensing tool] would be ideal, and then others to identify what sort of products that are there, and what type of safety equipment that we have to use to prevent... [contamination and absorption].

The case for the use of biosensors in the field of forensic science in Portugal has to take into consideration the frontier-like quality of forensic science—that is, scientific methods and techniques that are applied routinely to provide information to the “forensic,” or judicial, field. As previously remarked, the existing framework favours internationally standardized tools and techniques carried out by two institutions: the LPC and the INMLCF. The increasing specialization and division of labor within the forensic services provision means that people who collect traces at crime scenes do not usually engage in laboratory work, and those who produce forensic reports do not offer interpretations within the circumstances of the criminal event. Furthermore, the trial judge can always order additional forensic examinations by different experts at another laboratory (but usually under the same institution), and can only disregard the probative value of a forensic exam if there is another exam contradicting the first. Therefore, while there is a general optimism towards the use of new technologies at crime scenes, namely for presumptive testing of target analytes, evidence with probative value requires an “obligatory passage point” (Callon, 1986). The concept of an obligatory passage point refers to a point or mechanism within a network (herein, Portuguese forensics), where different actors and entities converge to achieve a common goal, or in this case, consensus on a new process and tool to be introduced.

While the use of biosensors for evidence-making in a legal context would be dependent upon European and national-level processes of standardization, validation, and acceptance by various categories and levels of actors, biosensors also have potential use-cases for the detection of traces to ensure occupational safety. In the scenario presented above, a biosensor to detect environmental hazards, toxins, or contaminants may not play a role in gathering or making evidence, but could be a useful tool for on-the-ground technicians to protect themselves and make sense of confusing and potentially hazardous scenes.

Biosensors for Environmental and Food Safety Monitoring

Research into biosensor applications in the area of environmental and food safety monitoring led our team to two main areas: the seafood/aquaculture sector, and the challenge of food fraud—here discussed primarily in relation to fish and honey. Potential applications include the use of biosensors for the monitoring of bivalves and Recirculated Aquaculture Systems (RAS) for farm-raised fish; fish species identification biosensors; biosensors to determine the botanical origin of honey; and biosensors integrated into “Smart” or “Active” packaging. Biosensors for environmental monitoring are a priority, but primarily in relation to upholding standards, ensuring food safety, and eliminating unwanted traces or adulteration in food.

Biosensors for bivalves and the monitoring of aquaculture beds

Portugal has the highest consumption of fisheries and aquaculture products in the European Union at 54.54kg live weight/per capita/per year (Directorate-General for Maritime Affairs and Fisheries, 2024). Globally, it ranks third. The enthusiasm for fish and seafood is not simply the result of geography, but

of historic, political, economic, cultural, religious and geographic factors (Almeida et al., 2015). Yet, such high levels of seafood consumption has economic, environmental, and health consequences (Murthy et al., 2023). To meet demand, Portugal imports more fish than it exports (Bjørndal et al., 2009; INE, 2024). As seafood and fish are among the foodstuffs most vulnerable to “food fraud” (Fox et al., 2018), not to mention food safety concerns, high consumption levels put Portuguese consumers at risk of exposure to seafood fraud. A decline in Portuguese fisheries has also spurred public and private investment in aquaculture and fish processing (Bjørndal et al., 2009), framed as an important segment of the “Blue Economy.” This broad category includes tourism, shipbuilding, marine renewable resources, and other sea-bound economic activities (Boriello et al., 2024).

Within this context, the safety of seafood and fish, including bivalves, has emerged as a speculative area of biosensor application. For example, Instituto Português do Mar e da Atmosfera (IPMA, the Portuguese Institute for Sea and Atmosphere) runs a shellfish monitoring program called Sistema Nacional de Monitorização de Moluscos Bivalves (SNMB, the National System for Monitoring Bivalve Molluscs). One of the responsibilities of the SNMB is to monitor deadly and dangerous neurotoxins in bivalves that can lead to various kinds of shellfish poisoning including paralytic shellfish poisoning, among others. The effects of consuming these toxins can range from gastroenteritis to death. Current validated methods for the detection of paralytic shellfish toxins include the mouse bioassay (a form of animal testing of food extracts), high performance liquid chromatography (HPLC), and Liquid Chromatography-Mass Spectrometry (LC-MS). The use of biosensors to detect toxins in bivalves is a potentially useful application of the device to address a number of challenges. This includes ensuring the safety of bivalves for human consumption, reducing the dependence on animal-based assays, and offering a more affordable and portable diagnostics solution than current diagnostic methods (Wei et al., 2023).

Biosensors may also be useful for the monitoring of aquaculture environments, especially for use in Recirculated Aquaculture Systems (RAS). RAS systems are land-based facilities (i.e., tanks) wherein fish are raised in closely monitored conditions. Unlike off-shore, sea-based aquaculture, RAS systems recirculate and reuse limited amounts of fresh water. Fish waste must be removed from the water, which must be closely monitored to ensure safe levels of ammonia and other toxins *and* nutrients. RAS systems are generally energy-intensive; at the same time, they allow for closer access to markets, production in areas far from the sea; and the mitigation of escapees—farm-raised fish that escape their beds to the ocean (more on these below).

As one interviewee at a research centre on the southern coast explained:

“But I think in terms of the application for us in terms of aquaculture, it's always on the fish safety for consumers, but also for the environmental conditions, which can be important for aquaculture-related aspects” (**Interviewee 12**).

They explained that these RAS aquaculture systems rely on closed-loop water filtration and treatment. As the health of farm-raised fish is directly linked to the quality of water in which they grow, water

monitoring and treatment should be important in this industry as it expands (**Interviewee 12**). Handheld water quality sensors are already in use in many places, however as Lindholm-Lehto (2023) points out, “...this requires staff, can be time consuming and is only possible during working hours” (p. 119). Here, a biosensor with continuous water monitoring capabilities could be enrolled as a labour-saving device, freed from the constraints of labour time. This theme frequently recurred across interviews, and will be explored in more depth in the discussion section below. The possibility of such a biosensor is reflected in the growing literature on sensor use in aquaculture, sometimes referred to as “Smart Aquaculture” (Hu et al., 2020; Su et al., 2020; Lindholm-Lehto, 2023). Although these biosensors are *not* in use in Portugal, and have only been tested here as part of an international project, they are in use in northern Europe and researchers hope to be able to adapt them to the warmer water and air temperatures of southern Europe (**Interviewee 12**).

Yet, several limitations and questions remain. In Norway, for example, there are currently no regulations governing water quality standards in RAS systems (Lindholm-Lehto, 2023). In Portugal, RAS systems are in the early stages; yet their implementation and “optimization” form part of the “Strategic Plan for Portuguese Aquaculture, 2021-2030” (European Commission, 2023). Without industry standards, backed by clear regulatory frameworks, the onus to invest, install, and maintain such a system would fall on producers. While large-scale producers might be able to afford such a cost, it could be outside the reach and capacity of small or medium-sized fish farmers operating within tight economic constraints. In an idealized framing, the benefits of such a biosensor would be to ensure that farm-raised fish grow in healthy, monitored, regulated environments, which would ideally accrue benefits to the many consumers of farm-raised fish in Portugal and beyond. In practice, if such systems are primarily accessible to large producers, and are installed with an eye towards cutting labour costs, the benefits would primarily accrue to the corporation and its clients, at the expense of aquaculture workers and smaller producers. Here is a case where the emergent technology may have markedly different outcomes depending on the context, which the following examples will continue to draw out.

Food Fraud, a Fish Species Biosensor, and the Future of Fish-Work

Another fish- and food-safety biosensor application identified is a *species verification* biosensor. In the European Economic Area, labelling errors of fish species can reach up to 70% (Miguéis et al., 2021). Mislabelling can be the result of error, but it is often deliberate and commonly referred to as “food fraud.” Sardines, for example, are especially liable to substitution for other small species of fish. A rapid, affordable, point-of-need biosensor that could verify fish species has been developed as part of the Consortium “EUFishTrust” (fisheustrust.org). This biosensor uses DNA to determine the species of a given fish. The goal of such a biosensor is to aid in attaining more accurate food labelling and increasing consumer confidence while protecting consumer safety.

Promoters of such technologies frame this kind of device as a *supply chain innovation*. This raises the question of: who is such a biosensor for? A fish species biosensor is unlikely to be used by a person shopping at a local fish market, or even at a supermarket. This is a tool that is first and foremost for food companies who source fish from multiple fisheries, often across international waters, and also

for actors and authorities concerned with food control and quality. In light of repeated public scandals about horse meat (Lawrence, 2013), marijuana in Haribo (Henley, 2025) and other kinds of food and resource fraud, some corporations are investing enormous sums of money in technology and other tracking tools to improve their large-scale logistics and audit their supply chains to safeguard consumer confidence (Subramanian, 2021). This kind of fish species biosensor may find traction among Portugal's industry-leading fish and seafood exporters for auditing and quality control purposes. While further research would be required to consider *how* such a device would impact work structures at such facilities, the expectation is that such a biosensor would allow a corporation to scale its verification abilities, and by extension enhance consumer trust.

The question of biosensor devices in relation to scale and scalability came up repeatedly in interviews. Take the following exchange:

Interviewer: Can I just continue in [their] line? Which is, then you would trust the device [the fish species biosensor] rather than the fishermen?

Interviewee 16: No, the fisherman, I trust him always. But the problem here is that he is not scalable.

At issue is not the skill, trust in, or knowledge capacity of the fisherman, but their “scalability.” Here are echoes of the aspirations of proponents of the RAS water-quality biosensor as a means of easing the labour requirements of current diagnostic practices. In another interview, a researcher explained how biosensors are explicitly imagined to intervene in the cost of pre-existing diagnostic processes and costs. They explained, “...if you [stick to] very old school diagnostic with titration analysers, you need to have an educated lab worker to do that. And it takes, I don't know how many samples that can handle, but like, one analyser takes a few hours, always. Of course, multiple patients and samples can be worked on at the same time, but it's still, someone has to do it...” (**Interviewee 5**). The reduction or elimination of the need for an “educated lab worker” is one of the anticipated effects of certain kinds of biosensors, linked to the acceleration of diagnostic speed, and industry-demands for solutions to meet their scalar ambitions.

The logics of scale and scalability, which surfaced repeatedly in discussions around biosensors and their interventions are not unique. Recently, Pfotenhauer et al. (2022) gave name to the “scalability zeitgeist,” a contemporary ordering logic underpinning public policy and innovation initiatives in the European Union and beyond. This political zeitgeist, the authors point out, is closely related to (at least) three other themes including tech solutionism, public experimentation, and future-oriented valuation practices. These ideologies are at play in the discourse and *mood* surrounding multiplex biosensors, although they do not mirror the current material reality of multiplex and other biosensing technologies, which cannot yet be manufactured on the scales sought by investors. Nevertheless, an identification of this zeitgeist, along with an exploration of what is *beyond* its imaginations and machinations, can help de-naturalize and better contextualize the priorities motivating current research, innovation, and funding initiatives and expand the range of possible interventions *and*

responses to social problems that can expand the contemporary EU-level focus and concentration of resources on technological and digital logics and solutions.

Namely, who or what is scalable, according to whom, where, and for what ends? The implicit and at times explicit view evoked in these exchanges is that people are not imagined or desired to be “scalable” (and hence worthy of investment in the form of capital). Either they are too expensive (the educated lab worker), too limited in availability to work (as in the case of water quality monitoring), or limited in number (fish workers with sufficient knowledge to sort species of fish). The idea that people are not “scalable” is a paradigm or logic, not in line with global demographic reality—to name one interpretation of what it might mean to “scale” a human. Investment in education offers another path towards imagining ways to “scale” or share, to name just one example, the embodied knowledge of fish workers that they might continue to reach generations still to come.

The Fish Market as a Site for the Negotiation of Knowledge and Power

If the above exchange flags some of the logics and politics of technology circulating in research and innovation circles, the following discussion comes from conversations with vendors and a food safety officer at a fish market in southern Portugal. It offers a different view onto the question of what categories of fish matter, and to whom. The fish species biosensor introduced above forwards biology over other categories of importance to people who eat fish. For some consumers of fish, biology is surely important. People want to know that the fish they are eating is what the package or vendor says it is.

The market’s food safety officer has been working at the market for many years, during which he has developed relationships with all of the people involved in buying and selling. He explained that customers are more concerned with whether a fish is *farmed* or *wild caught*. Vendors selling fish as wild caught are supposed to ensure they are, indeed, wild caught. The food safety officer explained that sometimes he spots what he suspects to be a farm-raised fish thrown in with wild-caught fish. He can tell, because of years of experience observing the differences in colour, size, shape, and flesh between farm-raised and wild fish. When a one-off fat farm fish is mixed in wild-caught fish, the inspector turns a blind eye. This is partially to give a break to the fish vendors and stay in good relations, but also partially due to a fact of fish: they swim, and can escape from aquaculture beds, blurring neat boundaries between farm-raised and wild fish.

During the conversation, we briefly introduced the concept of the biosensor in order to get a sense of the food safety officer’s perspective. He mentioned an openness to such a device, if it helped him to do his job better. In the context of this conversation, he also shared an anecdote that illustrates how power and knowledge do not have a linear or straightforward relation, and that emphasizes how caution and deliberation are important when introducing a technology designed to replace embodied knowledge and the kinds of workers mentioned above.

The food safety officer explained that one day, an ASAE employee visited the market. ASAE, the Autoridade de Segurança Alimentar e Económica (Economic and Food Safety Authority), is responsible

for the monitoring, surveillance, policing, and enforcement of economic activity in the food sector, and the regulation of economic activity and competition more broadly. The visitor from ASAE was not perceived to treat people in ways considered to be respectful. When the ASAE employee was inspecting the fish, our interviewee described the fish with wrong names and waited to see how the ASAE employee would react. The person repeated the same mistaken names. In the end, he revealed to the ASAE agent that he had been using wrong names as a subliminal way of questioning, through his knowledge, the ways in which ASAE staff were imposing their power. Knowledge was used as a means for negotiating power.

Caution: Humble vs Hubristic Devices

This informs a hypothetical reflection about the future and how the presence of a biosensor could transform such a situation. Only if a biosensor is accessible to fishery folks and sellers free of charge could it be used to build on empirical knowledge already in place. In this scenario, a humble device could become an instrument of producing knowledge, rather than of excluding knowledge. On the contrary, in a scenario wherein biosensors remain too expensive or hard to acquire, the possibilities of using knowledge as a means of negotiating power fades. Here a *technology of hubris* (Jasanoff 2007) could be used by a person who need not have embodied, deep knowledge about a certain topic or context in order to exert their authority over others, with potential serious consequences for small-scale producers and vendors.

These stories do not negate the context-dependent utility of a fish species biosensor; it is to point out that the biosensors that are currently being prototyped across the European Union represent *views from somewhere* that respond to concerns and demands of specific groups of people, and that this warrants caution. The categories intimately embedded into a fish species biosensor based on DNA, for example, better reflect the epistemologies of their designers (academic researchers and engineers), investors or potential investors (fisheries, food companies, local and state authorities) and consumers of exported fish than, for example, fish workers and fish consumers in local, coastal contexts. In an unequal, and increasingly unequal national and regional context, it is important to be clear and cautious about the uneven gains and losses the circulation of such devices may entail.

Technological devices provide partial information about very specific variables producing fragmented and decontextualized knowledge ("data"). They can also fail in the results as they are dependent on storage conditions and procedures of use and, even in the absence of such issues, they still can provide false results. In order for biosensors to be empowering, democratic, and a true innovation to food safety, they also need to be made available to the grassroots of the food and value chain. The categories of importance that drive technological innovation—here, for example, DNA and biology—are not shared or universal, yet they are often assumed to be by people within the biosensing field. What a device actually becomes is defined in the encounter with the users. In this sense, the encounter with the user should be conceived as another step in the production of technology and not a mere "application," it is the final step in the making of the device that itself continues to transform over time and cannot be predicted with certainty in advance.

Food Fraud, Authenticity, and Honey

Like fish and seafood, honey “fraud” is a persistent and well-documented problem in the European Union and beyond (Bruneau et al., 2024; García & Schwarzingler, 2021). Typically, it takes the form of adulteration. Taking honey as an example, it can be adulterated with sugar syrups and intentionally mislabelled regarding its floral or geographical origin. These practices pose challenges to consumer trust and confidence, but also significantly disadvantage small-scale producers and biodiversity-friendly apiculturists who are unable to compete with the price at which adulterated or mislabelled honey is sold. In this context, a honey-based biosensor developed in a bioelectronics laboratory offers a compelling, integrated approach to these three problems: it is designed to authenticate honey based on the honey’s unique “fingerprint,” using honey as both the analyte and a component of the device. This biosensor offers a low-energy, organic alternative to synthetic biosensors aimed to safeguard ecosystems and artisanal producers. Yet, as with the other applications discussed so far, its impact will depend on questions of access, institutional embedding, and the social and techno-political networks in which it might become enrolled.

In our search for biosensor applications for the environment, we remained far from our imaginations and expectations of biosensors for rivers, lakes, soil, air, and trees. The biosensor itself remained elusive and immaterial, evoked primarily in concepts that seemed very far from tangible settings. Yet, in a bioelectronics laboratory, an interviewee animated our study in two ways. In front of us, on the table, was a small device in the experimental phase, but that had a concrete existence. It was presented to us like this:

“This is now a sensor [...] in which honey [...] is not only the analyte, it’s part of the electronic component. If you don’t put honey there, the device does not work. You need to put honey. [...] Honey gives the ionic charges so the device can conduct electricity”
(Interviewee 16).

Here was a biosensor specifically tailored to sense honey, that also needed honey to work as a fluid to conduct the electric signal: a honey-based biosensor designed to analyse honey. This organic, honey-based honey-sensor was presented to us as useful for detecting the set of flowering plants used by bees to produce honey, and remarkably low-energy: “in solid state, you can go to 20, 40, 50 volts. But in electrolyte-gated transistors, you can work with really low energy” (Interviewee 16). Here was a biosensor that could perhaps defend not only ecosystems and biodiversity, but also the relations producers establish with bees and their pollination. This is particularly important for a context like Portugal, where honey is an important food and producers face competition and economic challenges.

In Portugal, honey holds cultural, economic, and ecological importance. Honey is used in traditional gastronomy (e.g., *broas de mel*, *bolo de mel*), traditional medicinal remedies, and as a sweetener. The consumption of honey has substantially increased in the country in the last decades, increasing continuously from 0,3 kg consumed/inhabitant/year in 1990 to 1,5 kg/inhabitant/year in 2015, since then it has varied between 1,0 and 1,5 kg/inhabitant/year (INE, 2025a). Production has increased

throughout the 20th century although it has suffered sharp decreases in the last years, particularly in 2017 due to numerous factors (INE, 2025b).

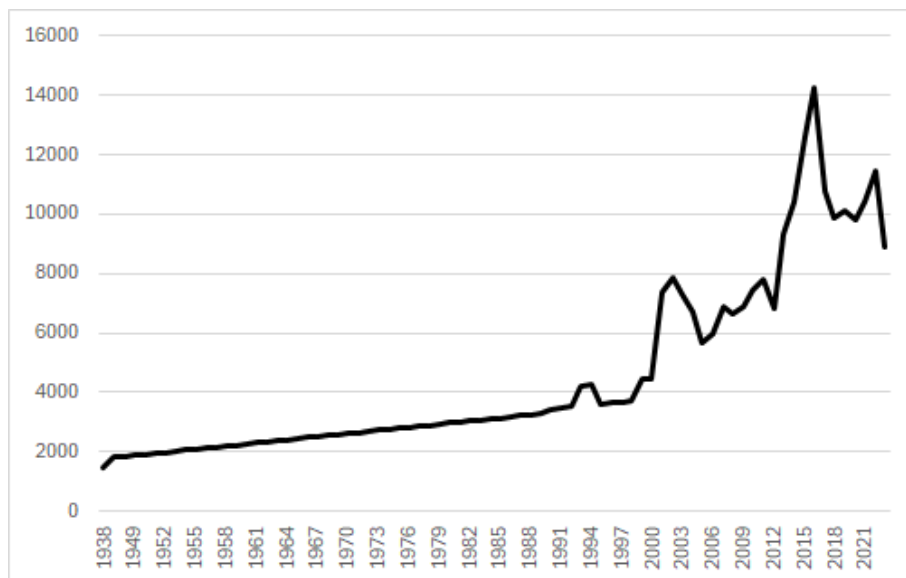


Figure 1 – Production of honey in Portugal in tons per year between 1938 and 2023 (Source: INE 2025b)

Portugal's rich and diverse melliferous flora offer a wide range of monofloral honeys across the country. The most emblematic monofloral honeys are lavender honey (*Lavandula stoechas*), heather honey (*Erica umbellata*), chestnut honey (*Castanea sativa*). Other monofloral honeys include rosemary (*Rosmarinus officinalis*), strawberry tree (*Arbutus unedo*), viper's bugloss (*Echium plantagineum*), Pennyroyal (*Mentha pulegium*), orange blossom (*Citrus sinensis*), thistle (*Carlina racemosa*), eucalyptus (*Eucalyptus* sp.) and sunflower (*Helianthus annuus*) (FNAP, 2017). Monofloral honeys usually command higher market prices, not only due to specific consumer demands, but also because production costs are higher, since beekeepers must carry out specific harvests (crests) for each blooming period to isolate each monofloral honey (FNAP, 2017).

The floral origin of honey is linked to organoleptic characteristics such as colour and flavour. According to its floral origin, several types of honey are classified. There is monofloral honey, which refers to a honey in which the pollen spectrum shows a single species comprising more than 45% of the pollen (exceptions to lavender and chestnut, which are considered as monofloral honeys when the percentages of their respective pollen types exceed 10% and 70%, respectively). Multifloral honey is obtained from the nectar of various plant species, in which no predominant characteristics of a specific plant stand out (FNAP, 2017).

Strategies for certifying honey have been promoted as important to face the challenges brought by the market and competitive honey prices. This strategy has been defended by projects like the BeeLand (<https://www.beeland.com.pt/>), funded by the European Union, and which brings together a wide variety of partners in Portugal: Federação Nacional dos Apicultores de Portugal (FNAP, National

Federation of Beekeepers of Portugal), Departamentos Regionais de Agricultura (DRAP, Regional Departments of Agriculture), cooperatives of producers (Lousãmel), association of producers (Meltagus), collaborative laboratories (MORE CoLAB), the agricultural industry, research centers (Instituto Politécnico de Bragança, Instituto Politécnico de Castelo Branco), and a private research centre (Raízes). One of the tasks of this project is to define methodologies for reliable and quick testing of the quality and authenticity of the honey and identify honey from regions that have Denominação de Origem Protegida status (DOP, Protected Designation of Origin).

The DOP designation is intended to identify a product from a specific location or region (or, in exceptional cases, from an entire country), whose quality or characteristics are essentially or exclusively due to a specific geographical environment (including its natural and human factors). All stages of its production must take place within the defined geographical area. In the case of honey, the fingerprint of the dominant flora that exists in a particular region that is left in the honey can help identify the DOP of a certain honey by examining whether it was produced from the pollinating activity of bees visiting the flowering plants growing in that region.

Regarding this possibility, the researcher developing honey-based biosensors for honey testing explained:

“In honey, we have a lot of compounds. We have minerals, we have sugars, we have bioactive compounds, we have proteins, we have enzymes. So, combining all of them. Let’s say, for example, that they have honey from rosemary, rosemary has a finger, a chemical fingerprint that is X percentage from this sugar, Y percentage from this amino acid, etc. So, when I put this, when I put it here as an electrolyte, the electrical equilibrium that will make, will be different from that of carob’s fruit [*Ceratonia siliqua*], for example, or other type of honey” (**Interviewee 16**).

It is convincing that biosensors could play a role in protecting honey producers, bees, and ecosystems all at once. Yet, it is also important to ground our reflection in the uncertainty from which expectations arise and ask questions that probe this optimistic vision. The key question is: who will be protected and who will be outrun by honey testing?

If honey authenticity biosensors are affordable for consumers and small-scale producers, they could have the potential to support producers, consumers, and bees. In this scenario, producers (invested in distinguishing their product from industrial honeys), consumers (seeking to purchase locally produced, high quality, DOP, or fraud-free honey), and bees (who benefit from support and protection of ecosystems) could all benefit. In this scenario, producers engaging in honey fraud, whether small, medium, or large-scale, could be disincentivized away from this practice. As with the scenario of the fish biosensor discussed above, this potential for decentralized control, ecosystem protection, and the defence of small-scale producers would be unattainable if the technology were to be seized by an exclusionary bureaucracy.

In this scenario in which large-scale honey producers benefit from biosensing techniques and technologies (who may also have the power to manipulate or influence regulations), then small honey producers, who form the majority of honey producers in Portugal, would not benefit from biosensing-based control. On the contrary, biosensors could function as another layer of market exclusion.

A few final questions may be important to deepen the reflection on the idea emerging during this study which is that biosensors cannot be disaggregated from a goal, a perspective and a motivation: How can honey biosensors protect communities of bees, flowers and people? What conditions can be put in place to avoid the market becoming the only shaping force? Can the technology of biosensors be concerned with final usage? Is it possible to direct technologies to specific users? These questions underscore the broader challenge of developing biosensors that are not only effective, but also do not grant already powerful economic and political actors more power and authority at the expense of artisanal producers.

Smart Packaging and Public Conceptions of Food Safety and Fraud

The so-called “Smart Packaging,” food packaging with embedded sensors, offers another area where biosensors may find application, albeit not multiplex biosensors. As one researcher and interviewee explained:

“So, we have now one prototype, we have a new project starting where we'll be going for another prototype, because we're also trying to ally this to active packaging. So, packaging that's able to contribute to the environment of the food. So, the food ecosystem, when we consider a package of food, and that we interface a sensor, so that we can in some way modulate the environment. But, at the same time, sense and, through the sensing of small volatiles, be able to create an electronic signal that could be picked up and received by a sensor that could be either a device in a phone, but that would tell us what's the status of the food in that pack” (**Interviewee 10**).

The idea is to use, as we understood:

“...very simple kinds of labels, which are basically, just like enzymes and substrates...But this is a very simple label. It costs, you know, 20 *cêntimos* [pennies], and you just can use it, not necessarily on all the food. Maybe you only need to put it on some of the food, but this is one of the concerns. It needs to be cheap enough to be deployable and it can't be something that's just for the rich company, countries” (**Interviewee 10**).

These sensors, and active or “smart” packaging more generally, are envisioned to help reduce food waste throughout the supply chain, and especially at the level of the household. Acknowledging the complexity in *both* the global food supply, and the relations between the priorities of producers and consumers, and the question of digital divides, this interviewee continued to characterize the challenges and biosensors’ imagined role therein:

“So, there have to be other measures clearly and there are other kinds of technologies which can be taking food waste and transforming it. So, we can upcycle, we can have alternative processing approaches that are not energy demanding, we can have shorter food supply chains, so we can think about other systems. So, I think there are a suite of things, but unquestionably, the biosensor has potential, which is quite significant in terms of, you know, producer profitability, and they're going to drive, in a way, availability of food and drive, maybe, part of the shift. So, I think, it's such a complex ecosystem that you have to support producers, so that they feel they're going to make a profit and that can be helped if you can assure that a bigger part of the production is sold. But, at the same time, you need to try and shift mindsets of consumers, mindsets of supermarkets, mindsets. So, and also train people, so that they understand and also, perhaps, you say biosensor, that you say, that's just for the elite, it's also for people to understand they're with us already, and they have potential, and they can be exploited in a way that can generate benefit in short-medium term, while some of the other developments that are needed will take longer. So, it's, yeah, it's challenging. It's not straightforward (Interviewee 10).

The hope or goal is that these kinds of biosensors, integrated into food packaging, will signal to consumers when a food item is safe to eat or not. This is held to be an improvement on tight “best buy” dates designed to reduce corporate risk because they can respond to the actual conditions of the food, rather than estimates that do not consider the conditions (environmental or otherwise) of the food supply chain from place to place. It is possible to imagine this type of biosensors helping consumers at the household level to reduce their waste. How such a biosensor would transform corporate risk and responsibility in relation to consumer wellbeing, however, is a significant question that could make the difference between the uptake and investment in such a biosensor, or its abandonment. At the same time, this kind of simple, qualitative biosensor embedded in packaging is perhaps one example of a biosensor that might (slowly) be accepted by consumers as its envisioned daily uses matches consumer habits.

In a recent study on Portuguese consumers’ conceptualizations of food fraud, Costa et al. (2024) found that the majority of surveyed consumers did not believe they had been exposed to food fraud, and reported that they do not engage in practices to reduce their exposure (Costa et al., 2024). When asked about possible solutions or responses to these challenges, respondents mentioned the intensification of inspection by authorities such as ASAE—albeit not without critique and limitation—and that they should adopt of more strategic consumer habits. A simple, food-safe, paper-based biosensor to detect bacteria integrated into already-existing packaging could provide some consumers with a helpful tool to navigate and better understand the safety of food and/or its contents. Its uptake might benefit from the fact that it does not present or demand a substantial change in buyers’ practices or habits.

Discussion

The BioAssembler Consortium and Expectations of Multiplex Biosensors

Reflexivity and subjectivity are cornerstones of interpretive qualitative research in the social sciences and humanities (SSH). Reflexivity refers to the practice of continuous critical reflection on how one's own position, assumptions, and background shape the research process and its outcomes. This includes formulating questions, selecting methods, and interpreting findings. Throughout this report, we have attempted to indicate the disjunctures and contradictions—moments of surprise, alongside our own expectations of what kinds of biosensors we would encounter. Subjectivity is the idea that perspective, perception, experience, bodily knowledge, relationships, social location, biography and many other visible and invisible (and conscious and unconscious) factors influence how meaning is made—in short, how research is crafted and knowledge ultimately produced (Sharp, 2020). Over the past three decades it has become commonplace for researchers in some SSH fields to engage in positional reflexivity by openly discussing how their research might reflect blind spots, biases, or interpretations rooted in dimensions of social location.

This is important; however, the approach adopted here is the practice of interpretive reflexivity: of trying to understand the meaning(s) and expectations of biosensors for members of the BioAssembler team, including the authors of this report (Lichterman, 2017). This is especially helpful in exploratory research contexts such as this, when the technology in question is still in formation. Multiplex biosensors are not only material devices in development, but promises, embedded in logics, imaginaries, and visions of a near-future Europe that is more competitive in this area than at present.

Funded by Horizon Europe (No 101070589), the BioAssembler consortium aims to “develop bio-intelligent manufacturing processes for multiplex MEMS (micro-electrical mechanical sensors) biosensors” (*Objectives*, BioAssembler; <https://bioassembler.eu/project/objectives/>) The overarching goal is “to develop a new generation of biosensors manufactured through a bio-intelligent process for rapid and massively parallel integration of biomolecules onto silicon wafers.” The aim of this project is to contribute to the transformation of the semiconductor industry, specifically through “the fusion of microelectronics and biotechnology” to strengthen “European leadership in this area and lead to increased business and work opportunities.” Increasing Europe's competitiveness in this area is an economic and political priority of the European Union.

It is important to emphasize that the aim of the BioAssembler consortium is to transform biosensor *manufacturing processes*, not biosensor applications per se. There is no established industrial process for the mass manufacturing of biosensors, which is the challenge at the core of the BioAssembler Consortium. Nevertheless, the applications of biosensors, actual or imagined, helps to clarify the stakes of the work being done in the BioAssembler consortium.

Adaptability and Applications

BioAssembler team members identified a range of potential applications for biosensors outside of the main focus areas of healthcare, health diagnostics, personalized medicine, and public health. The main industries that participants identified for biosensor application included: the food industry (food safety); state security surveillance (military, police); forensics; environmental monitoring; sports medicine and performance tracking; agriculture; animal health and veterinary medicine; water monitoring; and the cosmetics industry.

As one interviewee described this breadth, “Well, I think these sensors, this type of sensor could have a very wide range of applications. In my point of view, they could be related to help monitoring food safety, environmental monitoring. It depends on what biological element you will then attach to the sensor” (**Interviewee 7**). The adaptability of biosensors, achieved through the modification of the biosensor’s biological components to detect specific analytes, fuels interest and enthusiasm over biosensing potential in the present moment. Discerning between speculative and probable use cases has been one of the goals of this report, and can be further bolstered by examining the distinctive technical characteristics of these tools as they are currently being designed.

Speed, Portability, and Miniaturization: Key Characteristics of Multiplex Biosensors

Speed, portability, and miniaturization emerged as the three most important characteristics of multiplex biosensors according to members of the BioAssembler Consortium.

Point-of-care and point-of-need biosensors promise **speed**. Fast results are hoped to enable quicker decision-making, with implications for health, safety, and efficiency in a range of settings. Sepsis is a popular and useful example wherein rapid diagnosis with the help of a biosensor could both save lives and reduce emergency room costs. An example of a time-sensitive non-healthcare application is the daily collection of milk from small-scale farms by a milk cooperative or corporation. Milk is often collected farm-by-farm, and tested at a centralized location for bacteria, antibiotic levels, and other contaminants. When problems arise, entire batches of milk must be thrown out. This is a case where the daily testing of milk with a biosensing device on farms could allow for the early detection of contaminants, reducing the overall wastage of milk (**Interviewee 8**). As this scenario suggests, however, the introduction of a biosensor in this context could also shift burdens of cost, risk, and responsibility from the industrial dairy to the small-scale producer, depending on the dairy and context in question.

Portability is the second key feature of biosensors that render this accelerated speed possible. Wearable, implantable, and small-scale hand-held biosensors are envisioned to shift power from diagnostic laboratories to fieldworkers in everyday and urgent contexts. As one interviewee pointed out using the example of blood tests, “Currently, you take a blood sample, you package it, you ship it to a lab, outside the hospital or in the hospital. But it has to go there, and then it has to go back, and it's a lot of, basically, travel and nothing has been done yet. It hasn't, before anything happens the sample needs to reach its destination before, and nothing can happen” (**Interviewee 5**) Portability is held to reduce the time and cost of such routine diagnostics, alongside expanding the possibilities of

field-based and emergency medicine in out-of-reach places and contexts (e.g., mountains, vessels, conflict, and war).

Miniaturization, then, is what ultimately enables both speed and portability. Miniaturizing components to the nanoscale combined with innovations that allow for more analytes to be tested on a single chip, are the technical conditions that render these scenarios, at once perhaps “futuristic,” thinkable in the short- to medium-term. Researchers frame miniaturization as an engineering solution to meet industrial goals of reducing per-unit production costs to enable expanded scales of production, but it would be a mistake to view industrial priorities as the only driving force of miniaturization and other technological innovations in biosensing.

Fundamental or “Basic” Research and the Affective Dimensions of Research

In-depth qualitative interviews and sustained involvement with biosensing engineers and the broader biosensor community suggests that many are motivated by the affective dimensions of working in this area, including the idea of designing and building life-changing and life-saving technologies, and the awe that nano-biotechnological engineering and experimentation can offer. As one interviewee described, “So, in general, that's what I like most, the possibility of developing something that can have an impact on some people's lives” (**Interviewee 6**). Another explained, “But I must say, I profit more or I gain more from it, when I know that I am doing it for healthcare and for making life better for people, serving cancer, there are cancer patients to get better therapy, to make, to be in a project where we are working on organs...chips.. to get rid of animal testing” (**Interviewee 8**).

As for the affective dimensions of the technical work itself, the following quote demonstrates the fascination, enthusiasm, and excitement that basic or fundamental research can bring—even or especially when the applications, commercial or otherwise, are not known in advance:

“I really want to combine biochemistry and biomolecules into the silicon chips that make everything smaller and smaller, but still as sensitive as ever, and this is kind of a more, maybe I'm just fascinated with technology, and I'm trying to find, hopefully, find a good use for what we are developing. And I think there are, like I mentioned, this serology, measuring the presence of different antibodies. I think that's some very useful application. But there are not that many applications where you can measure tens of different analytes with the same technology, so that they would really be useful” (**Interviewee 1**).

Scientific researchers and engineers are beholden to funding structures at the national, regional, and international levels that shape how scientific research is presented, justified, framed, organized, and funded. In a research environment increasingly organized around outcomes, outputs, and applications, even when a researchers’ main focus is basic or fundamental research, they are often pressed to frame their work as applied in order to receive funding. The idea of “applications” may justify a given research project, but that does not mean it is the guiding question or prerogative of the scientists or engineers behind it. The gap or disjuncture between funding priorities and scientific

priorities is an historic and ongoing question and challenge in the European Union and beyond, but that bears ongoing engagement.

Data and the Politics of Concentration and Scale

So far, the focus has been on the production of biosensors and their applications. Yet, biosensors are devices that promise to produce something as well—data. As one interviewee explained, biosensors do not produce “big data.” They are better viewed as producing droplets of data in a stream that leads to a sea of big data:

“Our sensors, of course, produce kind of a lot of data and so I think it becomes big data just as a part of the other information where it, like, fits into the, adds a small bit, like you could say a droplet into the river. So, you can, the big data allows you to make a large picture, like there are these models for agricultural sensors that what will be the weather in six months, and so on, and so how will that affect the crops and will there be mycotoxins or not and blah blah. To get such kind of model or such prediction, you need a lot of data and maybe different sensors, and different forms all produce a small bit of data, and then when it all gets together that it's only then big data. So, I wouldn't say that our centre itself produces big data. It just produces some measurements, but together with measurements and data from many different sources, it is a part of the big data, and it can be helpful to think of how all these data can be used together for, and what can be the potential. How what it can provide. The advantages of all these data together for, and what can be the potential, what it can provide, the advantages of all these data together”
(Interviewee 4).

Some of this data is expected to afford immediate, actionable insights such as a sepsis diagnosis, a glucose reading, or reveal high levels of antibiotics in meat or milk. Much of the data, however, and its utility or applications are speculative. For example, networks of connected biosensors could allow for the establishment of better, more comprehensive algorithmic early warning systems, predictive diagnostics, and precision interventions (medical or otherwise). They could also expand the possibilities of algorithmic decision-making, dangerous automation, and data privacy and security concerns.

In short, there are contradictions in the way biosensors are discussed, envisioned, designed, and prototyped that this research has sought to draw out. Multiplex biosensors concentrate analytes, diagnostic functions, and nano-infrastructures to such a degree that they have become imperceptible to the naked eye, on silicon chips that are engineered to be ever-smaller, by specialists with increasingly advanced training and knowledge. On the one hand, a promise or hope of biosensor builders is to decentralize diagnostic capabilities from the lab to the field. This may happen in some contexts: fieldworkers may find utility in using biosensors, such as crime scene technicians identifying unknown and potentially hazardous substances. Simple, easy-to-manufacture biosensors may also hold potential for the expansion of citizen-and-subject science, of ordinary people examining,

measuring, and recording their environments and food, holding large-scale producers, institutions, and states accountable in unforeseen ways.

Yet, biosensors also concentrate power: in well-funded research laboratories, in companies, databases, and possibly in institutions of policing, surveillance, and control. The politics of concentration and the politics of scale are linked, in the sense that it is the technological concentration that makes the “scalability” possible, both in terms of power and capital. As the case of fish market suggests, if knowledgeable, experienced fish workers are excluded from the knowledge-making and technology-design process, they may find themselves increasingly vulnerable to, for example, state actors empowered with new technologies of knowledge-making that favour the priorities of large-scale food corporations over and above small-scale producers.

Conclusion

The production of biosensors must not be separated from their users. Funding technology that aims at monitoring bodies must take the people living in the bodies into account and not separate the process of construction of biosensors from the bodies that will be monitored. Similarly, if biosensors are used to monitor different ecologies and environments, spanning from a drop of sweat to a whole river basin, it is important to understand these ecologies as places that cannot be detached from their social, cultural and political contexts. How can this be achieved?

By dividing fundamental science from the development of devices. Strengthening the funding of fundamental science is able to support the interest and efforts of researchers that have a genuine interest in the nano-processes they study. The development of devices can use the outputs of fundamental science research, but this development must result from an engagement between social sciences, psychologists, communities, and research/technology developers (and others who wish to be involved in such processes). In this way, groups of people can attempt to direct the technology towards the development of devices in the service of the people and built with the people for ensuring people’s privacy, emotional and physical health, and democratic and free living with technologies that are able to respond to these objectives, rather than be fuelled by speculation and market prerogatives. This reflection has developed from the uncertainty evident across our interviews.

Importantly, biosensor research and design are still in a phase wherein new and innovative engagement with democracy and multi-disciplinarity can be attempted and achieved. Developments organized around the idea of “safety-by-design” as proposed by Van de Poel & Robaey (2017) may be relevant. These authors argue that while the approach of “safety-by-design” can make it harder to handle unforeseen risks, overlook the potential contributions from users, and be undemocratic, the benefits of designing with “responsibility for safety” in mind outweigh the potential drawbacks. This means designers should consider where responsibility for safety lies and structure the technology accordingly. Methodologically, a generative way to approach “safety-by-design,” and to re-think the

category of who gets to be a designer is to draw on speculative design methodologies (e.g., Dunne & Raby, 2013). Speculative design is a practice that aims to challenge the pre-eminence of commercialization in traditional design. In this approach, it is people, members of civil society, who are encouraged to communicate and decide what artefacts, tools, technologies, and ultimately future they want, as opposed to being driven by the priorities of investors and more powerful stakeholders. Practically speaking, this might look approaching organizations, associations, and institutions to form focus groups and discuss analytic and monitoring technologies generally, to understand where and what the challenges, needs, concerns, and hopes are, rather than attempt to define a conversation around biosensors as an unfamiliar object category.

While none of these proposals are easy or straightforward to achieve, taken together they could lead in the direction *away* from the ongoing generation of hubristic technologies in the direction of more humble technologies and knowledge-making processes.

Sources

- ALMEIDA, C., KARADZIC, V., & VAZ, S. (2015). THE SEAFOOD MARKET IN PORTUGAL: DRIVING FORCES AND CONSEQUENCES. *MARINE POLICY*, 61, 87–94. [HTTPS://DOI.ORG/10.1016/J.MARPOL.2015.07.012](https://doi.org/10.1016/j.marpol.2015.07.012)
- BASU, P., & KLEPEK, J. (2015). GEOGRAPHIES AND HISTORIES OF THE GREEN REVOLUTION: FROM GLOBAL FLOWS TO PLACE-BASED EXPERIENCES. IN *HANDBOOK ON THE GLOBALISATION OF AGRICULTURE* (PP. 237–254). EDWARD ELGAR PUBLISHING.
[HTTPS://WWW.ELGARONLINE.COM/EDCOLLCHAP/EDCOLL/9780857939821/9780857939821.00019.XML](https://www.elgaronline.com/EDCOLLCHAP/EDCOLL/9780857939821/9780857939821.00019.XML)
- BECK, U. (2002). THE TERRORIST THREAT. *WORLD RISK SOCIETY REVISITED. THEORY, CULTURE & SOCIETY*, 19(4), 39–55. [HTTPS://DOI.ORG/10.1177/0263276402019004003](https://doi.org/10.1177/0263276402019004003)
- BIOSENSORS FOR EUROPEAN ZOO NOTIC AGENTS: A CURRENT PORTUGUESE PERSPECTIVE. (N.D.). RETRIEVED JUNE 13, 2025, FROM [HTTPS://WWW.MDPI.COM/1424-8220/21/13/4547](https://www.mdpi.com/1424-8220/21/13/4547)
- BJØRNDAL, T., BRASÃO, A., RAMOS, J., & TUSVIK, A. (2016). FISH PROCESSING IN PORTUGAL: AN INDUSTRY IN EXPANSION. *MARINE POLICY*, 72, 94–106. [HTTPS://DOI.ORG/10.1016/J.MARPOL.2016.06.011](https://doi.org/10.1016/j.marpol.2016.06.011)
- BLOOMFIELD, B. P., & COOMBS, R. (1992). INFORMATION TECHNOLOGY, CONTROL AND POWER: THE CENTRALIZATION AND DECENTRALIZATION DEBATE REVISITED. *JOURNAL OF MANAGEMENT STUDIES*, 29(4), 459–459. [HTTPS://DOI.ORG/10.1111/J.1467-6486.1992.TB00674.X](https://doi.org/10.1111/j.1467-6486.1992.tb00674.x)
- BOER, B. DE. (2020). DISCOVERING SUBJECTIVITY IN THE TECHNOSYSTEM: DEVELOPING A CRITICAL POSITION TOWARDS CONTINGENT FORMS OF RATIONALITY. *TECHNÉ: RESEARCH IN PHILOSOPHY AND TECHNOLOGY*, 24(1–2), 62–82. [HTTPS://DOI.ORG/10.5840/TECHNE202026112](https://doi.org/10.5840/TECHNE202026112)
- BORRIELLO, A., CALVO SANTOS, A., CODINA LÓPEZ, L., FEYEN, L., GABORIEAU, N., GARAFFA, R., GHIANI, M., GUILLÉN, J., MC GOVERN, L., NORMAN, A., PERALTA BAPTISTA, A., PETRUCCO, G., PISTOCCHI, A., PLEGUEZUELO ALONSO, M., QUATRINI, S., TAPOGLOU, E., ABBAGNANO TRIONE, B., CAPPELL, R., CAVALIERE, F., ... VOUSDOKAS, M. I. (2024). THE EU BLUE ECONOMY REPORT 2024 (NO. KL-AR-24-001-EN-N).
[HTTPS://TRID.TRB.ORG/VIEW/2399813](https://trid.trb.org/View/2399813)
- BORUP, M., BROWN, NIK, KONRAD, KORNELIA, & VAN LENTE, H. (2006). THE SOCIOLOGY OF EXPECTATIONS IN SCIENCE AND TECHNOLOGY. *TECHNOLOGY ANALYSIS & STRATEGIC MANAGEMENT*, 18(3-4), 285-298.
[HTTPS://DOI.ORG/10.1080/09537320600777002](https://doi.org/10.1080/09537320600777002)
- BRUNEAU, E., ADOLPHE, C., DELSO, N. S., SPIEWOK, S., & RUBINIGG, M. (2024) EUROPEAN HONEY MARKET. EU POLLINATOR HUB. [HTTPS://APP.POLLINATORHUB.EU/DATASET-DISCOVERY/HNYMR172.0.0](https://app.pollinatorhub.eu/dataset-discovery/HNYMR172.0.0)
- CAGNANI, G. R., DA COSTA OLIVEIRA, T., MATTIOLI, I. A., SEDENHO, G. C., CASTRO, K. P. R., & CRESPILO, F. N. (2023). FROM RESEARCH TO MARKET: CORRELATION BETWEEN PUBLICATIONS, PATENT FILINGS, AND INVESTMENTS IN DEVELOPMENT AND PRODUCTION OF TECHNOLOGICAL INNOVATIONS IN BIOSENSORS. *ANALYTICAL AND BIOANALYTICAL CHEMISTRY*, 415(18), 3645–3653. [HTTPS://DOI.ORG/10.1007/S00216-022-04444-2](https://doi.org/10.1007/s00216-022-04444-2)
- CALLON, M. (1986). ELEMENTS OF A SOCIOLOGY OF TRANSLATION: DOMESTICATION OF THE SCALLOPS AND THE FISHERMEN OF ST BRIEUC BAY. IN J. LAW (ED.), *POWER, ACTION AND BELIEF: A NEW SOCIOLOGY OF KNOWLEDGE?* (PP. 196–223). ROUTLEDGE.

CAMPBELL, K. (2025). SMART BIOSENSING—PAST, PRESENT, AND FUTURE FOR FOOD & FEED DIAGNOSTICS. WORLD BIOSENSORS CONGRESS. LISBON, PORTUGAL.

CAMPOS, R., & BRITO, B. (2024). THE ROLE OF CITIZEN SCIENCE IN PUBLIC ENGAGEMENT WITH SOCIO-SCIENTIFIC DEBATES. ARPHA PROCEEDINGS, 6, 19-23. DOI: 10.3897/AP.E126291

CELIKBAS, E., BALABAN, S., EVRAN, S., COSKUNOL, H., & TIMUR, S. (2019). A BOTTOM-UP APPROACH FOR DEVELOPING APTASENSORS FOR ABUSED DRUGS: BIOSENSORS IN FORENSICS. BIOSENSORS, 9(4), ARTICLE 4. [HTTPS://DOI.ORG/10.3390/bios9040118](https://doi.org/10.3390/bios9040118)

CHARMAZ, K. (2006). CONSTRUCTING GROUNDED THEORY: A PRACTICAL GUIDE THROUGH QUALITATIVE ANALYSIS. SAGE PUBLICATIONS.

COSTA, M. J., SOUSA, I., PINTO MOURA, A., TEIXEIRA, J. A., & CUNHA, L. M. (2024). FOOD FRAUD CONCEPTUALIZATION: AN EXPLORATORY STUDY WITH PORTUGUESE CONSUMERS. JOURNAL OF FOOD PROTECTION, 87(7), 100301. [HTTPS://DOI.ORG/10.1016/J.JFP.2024.100301](https://doi.org/10.1016/J.JFP.2024.100301)

CRESSMAN, D. (2020). CONTINGENCY AND POTENTIAL: RECONSIDERING A DIALECTICAL PHILOSOPHY OF TECHNOLOGY. TECHNÉ: RESEARCH IN PHILOSOPHY AND TECHNOLOGY, 24(1-2), 138-158.

CURULLI, A. (2021). ELECTROCHEMICAL BIOSENSORS IN FOOD SAFETY: CHALLENGES AND PERSPECTIVES. MOLECULES, 26(10), 2940. [HTTPS://DOI.ORG/10.3390/molecules26102940](https://doi.org/10.3390/molecules26102940)

DAY, S., & LURY, C. (2016). BIOSENSING: TRACKING PERSONS. IN NAFUS, D. (ED.), QUANTIFIED: BIOSENSING TECHNOLOGIES IN EVERYDAY LIFE (PP. 43-66). MIT PRESS. [HTTPS://DOI.ORG/10.7551/MITPRESS/9780262034173.001.0001](https://doi.org/10.7551/MITPRESS/9780262034173.001.0001)

DE BOER, B. (2020). DISCOVERING SUBJECTIVITY IN THE TECHNOSYSTEM: DEVELOPING A CRITICAL POSITION TOWARDS CONTINGENT FORMS OF RATIONALITY. TECHNÉ: RESEARCH IN PHILOSOPHY AND TECHNOLOGY, 24(1-2), 62-82.

DIRECTORATE-GENERAL FOR MARITIME AFFAIRS AND FISHERIES (EUROPEAN COMMISSION) & EUMOFA. (2024). THE EU FISH MARKET: 2024 EDITION. PUBLICATIONS OFFICE OF THE EUROPEAN UNION. [HTTPS://DATA.EUROPA.EU/DOI/10.2771/9420236](https://data.europa.eu/doi/10.2771/9420236)

DUNNE, A., & RABY, F. (2013). SPECULATIVE EVERYTHING: DESIGN, FICTION, AND SOCIAL DREAMING. MIT PRESS.

ECSA (EUROPEAN CITIZEN SCIENCE ASSOCIATION). 2015. TEN PRINCIPLES OF CITIZEN SCIENCE. BERLIN. [HTTP://DOI.ORG/10.17605/OSF.IO/XPR2N](http://doi.org/10.17605/OSF.IO/XPR2N)

EDWARDS, P. N., & AND HECHT, G. (2010). HISTORY AND THE TECHNOLITICS OF IDENTITY: THE CASE OF APARTHEID SOUTH AFRICA. JOURNAL OF SOUTHERN AFRICAN STUDIES, 36(3), 619–639. [HTTPS://DOI.ORG/10.1080/03057070.2010.507568](https://doi.org/10.1080/03057070.2010.507568)

ENFSI. (2021). VISION OF THE EUROPEAN FORENSIC SCIENCE AREA 2030 - IMPROVING THE RELIABILITY AND VALIDITY OF FORENSIC SCIENCE AND FOSTERING THE IMPLEMENTATION OF EMERGING TECHNOLOGIES (VOL. 2025, ISSUE APRIL 2021, PP. 3–5).

EUROPEAN COMMISSION. (2023). SUMMARY PORTUGAL: STRATEGIC PLAN FOR PORTUGUESE AQUACULTURE 2021-2030." [HTTPS://AQUACULTURE.EC.EUROPA.EU/SYSTEM/FILES/2023-03/AAM_MNSP_PORTUGAL_0.PDF](https://aquaculture.ec.europa.eu/system/files/2023-03/AAM_MNSP_PORTUGAL_0.PDF)

FNAP. (2017). BOLETIM ESTATÍSTICO. O SECTOR APÍCOLA EM NÚMEROS: ANÁLISE E AVALIAÇÃO DA SITUAÇÃO EM PORTUGAL NA UNIÃO EUROPEIA E NO MERCADO MUNDIAL DE MEL. FEDERAÇÃO NACIONAL DOS APICULTORES DE PORTUGAL (FNAP).

FOX, M., MITCHELL, M., DEAN, M., ELLIOTT, C., & CAMPBELL, K. (2018). THE SEAFOOD SUPPLY CHAIN FROM A FRAUDULENT PERSPECTIVE. *FOOD SECURITY*, 10(4), 939–963. [HTTPS://DOI.ORG/10.1007/S12571-018-0826-Z](https://doi.org/10.1007/s12571-018-0826-z)

FUNTOWICZ, S. O., & RAVETZ, J. R. (1993). SCIENCE FOR THE POST-NORMAL AGE. *FUTURES*, 25(7), 739–755. [HTTPS://DOI.ORG/10.1016/0016-3287\(93\)90022-L](https://doi.org/10.1016/0016-3287(93)90022-L)

GARCÍA, N., & SCHWARZINGER, S. (2021). CHAPTER 15—HONEY FRAUD. IN R. S. HELLBERG, K. EVERSTINE, & S. A. SKLARE (EDS.), *FOOD FRAUD* (PP. 309–334). ACADEMIC PRESS. [HTTPS://DOI.ORG/10.1016/B978-0-12-817242-1.00019-1](https://doi.org/10.1016/B978-0-12-817242-1.00019-1)

GAVRILAŞ, S., URSACHI, C. ŞTEFAN, PERŢA-CRIŞAN, S., & MUNTEANU, F.-D. (2022). RECENT TRENDS IN BIOSENSORS FOR ENVIRONMENTAL QUALITY MONITORING. *SENSORS*, 22(4), ARTICLE 4. [HTTPS://DOI.ORG/10.3390/S22041513](https://doi.org/10.3390/s22041513)

GLASER, B. G., & STRAUSS, A. L. (1967). THE DISCOVERY OF GROUNDED THEORY: STRATEGIES FOR QUALITATIVE RESEARCH. ALDINE DE GRUYTER.

GOLDHABER, M. (1980). POLITICS AND TECHNOLOGY: MICROPROCESSORS AND THE PROSPECT OF A NEW INDUSTRIAL REVOLUTION. *POLITICS AND TECHNOLOGY: MICROPROCESSORS AND THE PROSPECT OF A NEW INDUSTRIAL REVOLUTION*, 10(4), 9–32.

GONÇALVES, M. E. (2012). RISK SOCIETY AND THE GOVERNANCE OF INNOVATION IN EUROPE: OPENING THE BLACK BOX? *SCIENCE AND PUBLIC POLICY*, 31(6), 457–464. [HTTPS://DOI.ORG/10.1007/978-94-007-1433-5](https://doi.org/10.1007/978-94-007-1433-5)

GRANJA, R. (2021). THE INVISIBLE IMPLICATIONS OF TECHNO-OPTIMISM OF ELECTRONIC MONITORING IN PORTUGAL (R. GRANJA, TRANS.). *COMUNICAÇÃO E SOCIEDADE*, 40, ARTICLE 40.

GREGORY, J., & BOWKER, G. C. (2016). THE DATA CITIZEN, THE QUANTIFIED SELF, AND PERSONAL GENOMICS. [HTTPS://DOI.ORG/10.7551/MITPRESS/10293.003.0017](https://doi.org/10.7551/MITPRESS/10293.003.0017)

GRIESCHE, C., & BAEUMNER, A. J. (2020). BIOSENSORS TO SUPPORT SUSTAINABLE AGRICULTURE AND FOOD SAFETY. *TRAC TRENDS IN ANALYTICAL CHEMISTRY*, 128, 115906. [HTTPS://DOI.ORG/10.1016/J.TRAC.2020.115906](https://doi.org/10.1016/J.TRAC.2020.115906)

HAKLAY, M., KÖNIG, A., MOUSTARD, F., & ASPEE, N. (2023). CITIZEN SCIENCE AND POST-NORMAL SCIENCE’S EXTENDED PEER COMMUNITY: IDENTIFYING OVERLAPS BY MAPPING TYPOLOGIES. *FUTURES*, 150, 103178. [HTTPS://DOI.ORG/10.1016/J.FUTURES.2023.103178](https://doi.org/10.1016/J.FUTURES.2023.103178)

HENLEY, J. (2025, MAY 29). HARIBO RECALLS SWEETS IN THE NETHERLANDS AFTER TRACES OF CANNABIS FOUND. *THE GUARDIAN*. [HTTPS://WWW.THEGUARDIAN.COM/WORLD/2025/MAY/29/HARIBO-RECALLS-SWEETS-IN-THE-NETHERLANDS-AFTER-TRACES-OF-CANNABIS-FOUND](https://www.theguardian.com/world/2025/may/29/haribo-recalls-sweets-in-the-netherlands-after-traces-of-cannabis-found)

HU, Z., LI, R., XIA, X., YU, C., FAN, X., & ZHAO, Y. (2020). A METHOD OVERVIEW IN SMART AQUACULTURE. *ENVIRONMENTAL MONITORING AND ASSESSMENT*, 192(8), 493. [HTTPS://DOI.ORG/10.1007/S10661-020-08409-9](https://doi.org/10.1007/s10661-020-08409-9)

HUANG, C.-W., LIN, C., NGUYEN, M. K., HUSSAIN, A., BUI, X.-T., & NGO, H. H. (2023). A REVIEW OF BIOSENSOR FOR ENVIRONMENTAL MONITORING: PRINCIPLE, APPLICATION, AND CORRESPONDING ACHIEVEMENT OF SUSTAINABLE DEVELOPMENT GOALS. *BIOENGINEERED*, 14(1), 58–80. [HTTPS://DOI.ORG/10.1080/21655979.2022.2095089](https://doi.org/10.1080/21655979.2022.2095089)

INE (2024). ESTATÍSTICAS DA PESCA – 2024. INSTITUTO NACIONAL DE ESTATÍSTICA. [HTTPS://WWW.INE.PT/XPORTAL/XMAIN?XPID=INE&XPGID=INE_DESTAQUES&DESTAQUESDEST_BOUI=706295176&DESTAQUESMOD=2&XLANG=PT](https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=INE_DESTAQUES&DESTAQUESDEST_BOUI=706295176&DESTAQUESMOD=2&XLANG=PT)

INE. (2025A). CONSUMO HUMANO DE MEL PER CAPITA (KG/ HAB.) -ANUAL. INSTITUTO NACIONAL DE ESTATÍSTICA. [HTTPS://WWW.INE.PT/XPORTAL/XMAIN?XPID=INE&XPGID=INE_INDICADORES&INDOCCORR=0000202&CONTEXTO=BD&SELTAB=TAB2](https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=INE_INDICADORES&INDOCCORR=0000202&CONTEXTO=BD&SELTAB=TAB2)

INE. (2025B). PRODUÇÃO DE MEL (T)—ANUAL. INSTITUTO NACIONAL DE ESTATÍSTICA. [HTTPS://WWW.INE.PT/XPORTAL/XMAIN?XPID=INE&XPGID=INE_INDICADORES&INDOCCORR=0000202&CONTEXTO=BD&SELTAB=TAB2](https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=INE_INDICADORES&INDOCCORR=0000202&CONTEXTO=BD&SELTAB=TAB2)

JASANOFF, S. (2007). TECHNOLOGIES OF HUMILITY. *NATURE*, 450(7166), 33–33. [HTTPS://DOI.ORG/10.1038/450033A](https://doi.org/10.1038/450033A)

JUSTINO, C. I. L., DUARTE, A. C., & ROCHA-SANTOS, T. A. P. (2017). RECENT PROGRESS IN BIOSENSORS FOR ENVIRONMENTAL MONITORING: A REVIEW. *SENSORS*, 17(12), ARTICLE 12. [HTTPS://DOI.ORG/10.3390/s17122918](https://doi.org/10.3390/s17122918)

KOEHLER, J. J. (1993). ERROR AND EXAGGERATION IN THE PRESENTATION OF DNA EVIDENCE AT TRIAL (SSRN SCHOLARLY PAPER NO. 1432065). SOCIAL SCIENCE RESEARCH NETWORK. [HTTPS://PAPERS.SSRN.COM/ABSTRACT=1432065](https://papers.ssrn.com/abstract=1432065)

KØNIG, N., BØRSEN, T., & EMMECHE, C. (2017). THE ETHOS OF POST-NORMAL SCIENCE. *FUTURES*, 91, 12–24. [HTTPS://DOI.ORG/10.1016/J.FUTURES.2016.12.004](https://doi.org/10.1016/j.futures.2016.12.004)

KRAGH-FURBO, M., MACKENZIE, A., MORT, M., & ROBERTS, C. (2016). DO BIOSENSORS BIOMEDICALIZE? SITES OF NEGOTIATION IN DNA-BASED BIOSENSING DATA PRACTICES. [HTTPS://DOI.ORG/10.7551/MITPRESS/10293.003.0004](https://doi.org/10.7551/MITPRESS/10293.003.0004)

KRUSE, C. (2015). THE SOCIAL LIFE OF FORENSIC EVIDENCE. UNIV OF CALIFORNIA PRESS.

LAWRENCE, F. (2013, FEBRUARY 15). HORSEMEAT SCANDAL: THE ESSENTIAL GUIDE. THE GUARDIAN. [HTTPS://WWW.THEGUARDIAN.COM/UK/2013/FEB/15/HORSEMEAT-SCANDAL-THE-ESSENTIAL-GUIDE](https://www.theguardian.com/uk/2013/feb/15/horsemeat-scandal-the-essential-guide)

LEMENINEN, S., & WESTERLUND, M. (2019). LIVING LABS: FROM SCATTERED INITIATIVES TO A GLOBAL MOVEMENT. *CREATIVITY AND INNOVATION MANAGEMENT*, 28(2), 250-264. [HTTPS://DOI.ORG/10.1111/CAIM.12310](https://doi.org/10.1111/caim.12310)

LEUNG, C. M., DE HAAN, P., RONALDSON-BOUCHARD, K., KIM, G.-A., KO, J., RHO, H. S., CHEN, Z., HABIBOVIC, P., JEON, N. L., TAKAYAMA, S., SHULER, M. L., VUNJAK-NOVAKOVIC, G., FREY, O., VERPOORTE, E., & TOH, Y.-C. (2022). A GUIDE TO THE ORGAN-ON-A-CHIP. *NATURE REVIEWS METHODS PRIMERS*, 2(1), 33. [HTTPS://DOI.ORG/10.1038/s43586-022-00118-6](https://doi.org/10.1038/s43586-022-00118-6)

LICHTERMAN, P. (2017). INTERPRETIVE REFLEXIVITY IN ETHNOGRAPHY. *ETHNOGRAPHY*, 18(1), 35-45.

[HTTPS://DOI.ORG/10.1177/1466138115592418](https://doi.org/10.1177/1466138115592418)

LINDHOLM-LEHTO, P. (2023). WATER QUALITY MONITORING IN RECIRCULATING AQUACULTURE SYSTEMS. *AQUACULTURE, FISH AND FISHERIES*, 3(2), 113–131. [HTTPS://DOI.ORG/10.1002/aff2.102](https://doi.org/10.1002/aff2.102)

LUONG, J. H. T., MALE, K. B., & GLENNON, J. D. (2008). BIOSENSOR TECHNOLOGY: TECHNOLOGY PUSH VERSUS MARKET PULL. *BIOTECHNOLOGY ADVANCES*, 26(5), 492–500. [HTTPS://DOI.ORG/10.1016/J.BIOTECHADV.2008.05.007](https://doi.org/10.1016/j.biotechadv.2008.05.007)

MACHADO, H., & SANTOS, F. (2011). POPULAR PRESS AND FORENSIC GENETICS IN PORTUGAL: EXPECTATIONS AND DISAPPOINTMENTS REGARDING TWO CASES OF MISSING CHILDREN. *PUBLIC UNDERSTANDING OF SCIENCE (BRISTOL, ENGLAND)*, 20(3), 303–318. [HTTPS://DOI.ORG/10.1177/0963662509336710](https://doi.org/10.1177/0963662509336710)

MAGER, A., & KATZENBACH, C. (2021). FUTURE IMAGINARIES IN THE MAKING AND GOVERNING OF DIGITAL TECHNOLOGY: MULTIPLE, CONTESTED, COMMODIFIED. *NEW MEDIA & SOCIETY*, 23(2), 223–236. [HTTPS://DOI.ORG/10.1177/1461444820929321](https://doi.org/10.1177/1461444820929321)

MCGOLDRICK, L. K., & HALÁMEK, J. (2020). RECENT ADVANCES IN NONINVASIVE BIOSENSORS FOR FORENSICS, BIOMETRICS, AND CYBERSECURITY. *SENSORS*, 20(21), ARTICLE 21. [HTTPS://DOI.ORG/10.3390/s20215974](https://doi.org/10.3390/s20215974)

MIGUÉIS, S. DA C., TAVARES, A. P. M., MARTINS, G. V., FRASCO, M. F., & SALES, M. G. F. (2021). BIOSENSORS FOR EUROPEAN ZOOLOGICAL AGENTS: A CURRENT PORTUGUESE PERSPECTIVE. *SENSORS*, 21(13), ARTICLE 13. [HTTPS://DOI.ORG/10.3390/s21134547](https://doi.org/10.3390/s21134547)

MISERA, J., MELCHERT, J., & BORK-HÜFFER, T. (2024). BIOSENSING AND BIOSENSORS—TERMINOLOGIES, TECHNOLOGIES, THEORIES AND ETHICS. *GEOGRAPHY COMPASS*, 18(11), e70007. [HTTPS://DOI.ORG/10.1111/gec3.70007](https://doi.org/10.1111/gec3.70007)

MORALES-NARVÁEZ, E., & DINCER, C. (2020). THE IMPACT OF BIOSENSING IN A PANDEMIC OUTBREAK: COVID-19. *BIOSENSORS AND BIOELECTRONICS*, 163, 112274. [HTTPS://DOI.ORG/10.1016/J.BIOS.2020.112274](https://doi.org/10.1016/j.bios.2020.112274)

MORGAN, J. (2023). WRONGFUL CONVICTIONS AND CLAIMS OF FALSE OR MISLEADING FORENSIC EVIDENCE. *JOURNAL OF FORENSIC SCIENCES*, 68(3), 908–961. [HTTPS://DOI.ORG/10.1111/1556-4029.15233](https://doi.org/10.1111/1556-4029.15233)

MURPHY, E. (2006). THE NEW FORENSICS: CRIMINAL JUSTICE, FALSE CERTAINTY, AND THE SECOND GENERATION OF SCIENTIFIC EVIDENCE (SSRN SCHOLARLY PAPER NO. 896128). SOCIAL SCIENCE RESEARCH NETWORK. [HTTPS://PAPERS.SSRN.COM/ABSTRACT=896128](https://papers.ssrn.com/abstract=896128)

MURTHY, A., GALLI, A., MADEIRA, C., & MORENO PIRES, S. (2023). CONSUMER ATTITUDES TOWARDS FISH AND SEAFOOD IN PORTUGAL: OPPORTUNITIES FOR FOOTPRINT REDUCTION. *SUSTAINABILITY*, 15(2), ARTICLE 2. [HTTPS://DOI.ORG/10.3390/su15021363](https://doi.org/10.3390/su15021363)

NAFUS, D. (ED.). (2016). QUANTIFIED: BIOSENSING TECHNOLOGIES IN EVERYDAY LIFE. MIT PRESS. [HTTPS://DOI.ORG/10.7551/MITPRESS/9780262034173.001.0001](https://doi.org/10.7551/mitpress/9780262034173.001.0001)

NAFUS, D. (2016). INTRODUCTION. IN NAFUS, D. (ED.), QUANTIFIED: BIOSENSING TECHNOLOGIES IN EVERYDAY LIFE (PP. IX-XXXI). MIT PRESS. [HTTPS://DOI.ORG/10.7551/MITPRESS/9780262034173.001.0001](https://doi.org/10.7551/mitpress/9780262034173.001.0001)

NEWMAN, J. D., & TURNER, A. P. (2007). HISTORICAL PERSPECTIVE OF BIOSENSOR AND BIOCHIP

DEVELOPMENT. HANDBOOK OF BIOSENSORS AND BIOCHIPS, WILEY-INTERSCIENCE.

NISSENBAUM, H., & PATTERSON, H. (2016). BIOSENSING IN CONTEXT: HEALTH PRIVACY IN A CONNECTED WORLD. [HTTPS://DOI.ORG/10.7551/MITPRESS/10293.003.0009](https://doi.org/10.7551/mitpress/10293.003.0009)

OBJECTIVES – BIOASSEMBLER. (N.D.). RETRIEVED JUNE 13, 2025, FROM [HTTPS://BIOASSEMBLER.EU/PROJECT/OBJECTIVES/](https://bioassembler.eu/project/objectives/)

OLSEN, J.-K. B., & CREASE, R. P. (2015). TECHNOSCIENCE AND POSTPHENOMENOLOGY: THE MANHATTAN PAPERS. LEXINGTON BOOKS.

PAL, M. K., AHMED, M. U., & CAMPBELL, K. (2024). BIOSENSORS FOR FOODBORNE PATHOGEN DETECTION: A RAPID DETECTION APPROACH. ELSEVIER.

PARK, E. (2024). INFRASTRUCTURAL ATTACHMENTS: AUSTERITY, SOVEREIGNTY, AND EXPERTISE IN KENYA. DUKE UNIVERSITY PRESS.

PATEL, R. (2013). THE LONG GREEN REVOLUTION. THE JOURNAL OF PEASANT STUDIES, 40(1), 1–63. [HTTPS://DOI.ORG/10.1080/03066150.2012.719224](https://doi.org/10.1080/03066150.2012.719224)

PAUNOV C, PLANES-SATORRA S. SCIENCE, TECHNOLOGY AND INNOVATION IN THE TIME OF COVID-19. OECD SCI TECHNOL IND POLICY PAP. 2021;99(99). [HTTPS://DOI.ORG/10.1787/234A00E5-EN](https://doi.org/10.1787/234a00e5-en).

PFOTENHAUER, S., LAURENT, B., PAPAGEORGIOU, K., & STILGOE, AND J. (2022). THE POLITICS OF SCALING. SOCIAL STUDIES OF SCIENCE, 52(1), 3–34. [HTTPS://DOI.ORG/10.1177/03063127211048945](https://doi.org/10.1177/03063127211048945)

POPULAR SWEETS RECALLED IN BELGIUM OVER CANNABIS IN DUTCH GUMMIES. (16:36:31 +02:00). EURONEWS. [HTTPS://WWW.EURONEWS.COM/MY-EUROPE/2025/06/02/HARIBO-SWEETS-RECALLED-IN-BELGIUM-AFTER-CANNABIS-FOUND-IN-DUTCH-GUMMIES](https://www.euronews.com/my-europe/2025/06/02/haribo-sweets-recalled-in-belgium-after-cannabis-found-in-dutch-gummies)

QUINLAN, A. (2021). THE RAPE KIT’S PROMISE: TECHNO-OPTIMISM IN THE FIGHT AGAINST THE BACKLOG. SCIENCE AS CULTURE, 30(3), 440–464. [HTTPS://DOI.ORG/10.1080/09505431.2020.1846696](https://doi.org/10.1080/09505431.2020.1846696)

REBAUX, O., BAYLON, A., ROUX, C., DELÉMONT, O., LOCK, E., ZINGG, C., & MARGOT, P. (2010). INTELLIGENCE-LED CRIME SCENE PROCESSING. PART I: FORENSIC INTELLIGENCE. FORENSIC SCIENCE INTERNATIONAL, 195(1), 10–16. [HTTPS://DOI.ORG/10.1016/J.FORSIINT.2009.10.027](https://doi.org/10.1016/j.forsciint.2009.10.027)

RODRIGUEZ-MOZAZ, S., ALDA, M. J. L. DE, MARCO, M.-P., & BARCELÓ, D. (2005). BIOSENSORS FOR ENVIRONMENTAL MONITORING: A GLOBAL PERSPECTIVE. TALANTA, 65(2), 291–297. [HTTPS://DOI.ORG/10.1016/J.TALANTA.2004.07.006](https://doi.org/10.1016/j.talanta.2004.07.006)

SAKS, M. J., & KOEHLER, J. J. (2005). THE COMING PARADIGM SHIFT IN FORENSIC IDENTIFICATION SCIENCE. SCIENCE (NEW YORK, N.Y.), 309(5736), 892–895. [HTTPS://DOI.ORG/10.1126/SCIENCE.1111565](https://doi.org/10.1126/science.1111565)

SAKS, M. J., & KOEHLER, J. J. (2008). THE INDIVIDUALIZATION FALLACY IN FORENSIC SCIENCE EVIDENCE. VANDERBILT UNIVERSITY LAW REVIEW, 61(1), 199–219. [HTTPS://DOI.ORG/10.1016/J.FORSIINT.2004.07.005](https://doi.org/10.1016/j.forsciint.2004.07.005)

SALTELLI, A. (2024). WHAT IS POST-NORMAL SCIENCE? A PERSONAL ENCOUNTER. FOUNDATIONS OF SCIENCE, 29(4), 945–954. [HTTPS://DOI.ORG/10.1007/S10699-023-09932-X](https://doi.org/10.1007/s10699-023-09932-x)

SANTOS, F. (2014). MAKING SENSE OF THE STORY - THE DIALOGUES BETWEEN THE POLICE AND FORENSIC LABORATORIES IN THE CONSTRUCTION OF DNA EVIDENCE. *NEW GENETICS AND SOCIETY*, 33(2), 181-203. DOI: 10.1080/14636778.2014.916186

SANTOS, F., & COSTA, S. (2024). CRIME IN A PRISON CELL: EPISTEMIC CULTURES AND INSTITUTIONAL NEUTRALITY IN AN INQUISITORIAL SETTING. *CRIME, MEDIA, CULTURE*, 20(3), 250–268. [HTTPS://DOI.ORG/10.1177/17416590231196131](https://doi.org/10.1177/17416590231196131)

SHARP, J. (2020). SUBJECTIVITY. IN A. KOBAYASHI (ED.), *INTERNATIONAL ENCYCLOPEDIA OF HUMAN GEOGRAPHY* (PP. 117–120). ELSEVIER INC. [HTTPS://DOI.ORG/10.1016/B978-0-08-102295-5.10869-8](https://doi.org/10.1016/B978-0-08-102295-5.10869-8)

SHERMAN, J. (2016). DATA IN THE AGE OF DIGITAL REPRODUCTION: READING THE QUANTIFIED SELF THROUGH WALTER BENJAMIN. [HTTPS://DOI.ORG/10.7551/MITPRESS/10293.003.0005](https://doi.org/10.7551/MITPRESS/10293.003.0005)

SINGH, A. R., & SINGH, A. P. (2025). MARKET TRENDS OF BIOSENSORS. IN *SMART AND INTELLIGENT NANOSTRUCTURED MATERIALS FOR NEXT-GENERATION BIOSENSORS* (PP. 315-335). ELSEVIER. [HTTPS://DOI.ORG/10.1016/B978-0-443-19146-6.00010-1](https://doi.org/10.1016/B978-0-443-19146-6.00010-1)

SOETE, L., VERSPAGEN, B., & TER WEEL, B. (2010). *SYSTEMS OF INNOVATION* (VOL. 2, PP. 1159–1180). ELSEVIER. [HTTPS://DOI.ORG/10.1016/S0169-7218\(10\)02011-3](https://doi.org/10.1016/S0169-7218(10)02011-3)

SPECULATIVE EVERYTHING. (N.D.). MIT PRESS. RETRIEVED JUNE 13, 2025, FROM [HTTPS://MITPRESS.MIT.EDU/9780262019842/SPECULATIVE-EVERYTHING/](https://mitpress.mit.edu/9780262019842/speculative-everything/)

STAHL, W. A. (2009). *GOD AND THE CHIP: RELIGION AND THE CULTURE OF TECHNOLOGY*. WILFRID LAURIER UNIV. PRESS.

STRATHERN, M. (1988). *THE GENDER OF THE GIFT: PROBLEMS WITH WOMEN AND PROBLEMS WITH SOCIETY IN MELANESIA* (VOL. 6). UNIV OF CALIFORNIA PRESS.

SU, X., SUTARLIE, L., & LOH, X. J. (2020). SENSORS, BIOSENSORS, AND ANALYTICAL TECHNOLOGIES FOR AQUACULTURE WATER QUALITY. *RESEARCH* (WASHINGTON, D.C.), 2020, 8272705. [HTTPS://DOI.ORG/10.34133/2020/8272705](https://doi.org/10.34133/2020/8272705)

SUBRAMANIAN, S. (2021, SEPTEMBER 16). FOOD FRAUD AND COUNTERFEIT COTTON: THE DETECTIVES UNTANGLING THE GLOBAL SUPPLY CHAIN. *THE GUARDIAN*. [HTTPS://WWW.THEGUARDIAN.COM/NEWS/2021/SEP/16/FOOD-FRAUD-COUNTERFEIT-COTTON-DETECTIVES-UNTANGLING-GLOBAL-SUPPLY-CHAIN](https://www.theguardian.com/news/2021/sep/16/food-fraud-counterfeit-cotton-detectives-untangling-global-supply-chain)

TAYLOR, A. (2016). DATA, (BIO)SENSING, AND (OTHER-)WORLDLY STORIES FROM THE CYCLE ROUTES OF LONDON. [HTTPS://DOI.ORG/10.7551/MITPRESS/10293.003.0016](https://doi.org/10.7551/MITPRESS/10293.003.0016)

TRUMP, B., CUMMINGS, C., KLASA, K., GALAITSI, S., & LINKOV, I. (2023). GOVERNING BIOTECHNOLOGY TO PROVIDE SAFETY AND SECURITY AND ADDRESS ETHICAL, LEGAL, AND SOCIAL IMPLICATIONS. *FRONTIERS IN GENETICS*, 13. [HTTPS://DOI.ORG/10.3389/FGENE.2022.1052371](https://doi.org/10.3389/fgene.2022.1052371)

TURNER, A., KARUBE, I., & WILSON, G. S. (1987). *BIOSENSORS: FUNDAMENTALS AND APPLICATIONS*. OXFORD UNIVERSITY PRESS.

VALENTE, B., PINTO, H., PEREIRA, T. S., & CAMPOS, R. (2024). *EXPLORING BIOSENSORS' SCIENTIFIC PRODUCTION*

AND RESEARCH PATTERNS: A BIBLIOMETRIC ANALYSIS. *SENSORS*, 24(10), ARTICLE 10.
[HTTPS://DOI.ORG/10.3390/s24103082](https://doi.org/10.3390/s24103082)

VAN DE POEL, I., & ROBAEY, Z. (2017). SAFE-BY-DESIGN: FROM SAFETY TO RESPONSIBILITY. *NANOETHICS*, 11(3), 297–306. [HTTPS://DOI.ORG/10.1007/s11569-017-0301-x](https://doi.org/10.1007/s11569-017-0301-x)

VERBEEK, P. P. (2016). TOWARD A THEORY OF TECHNOLOGICAL MEDIATION: A PROGRAM FOR POSTPHENOMENOLOGICAL RESEARCH. IN *TECHNOSCIENCE AND POSTPHENOMENOLOGY: THE MANHATTAN PAPERS* (P. 189). LEXINGTON BOOKS.

VESTAD, M. (2024). THE PERSISTENT ATTRACTIONS OF LOW-TECH: CHALLENGING THE EFFICIENCY PARADIGM OF FORENSIC TECHNOLOGY. *INTERNATIONAL JOURNAL OF POLICE SCIENCE AND MANAGEMENT*. [HTTPS://DOI.ORG/10.1177/14613557241231164](https://doi.org/10.1177/14613557241231164)

WANG, X., LUO, Y., HUANG, K., & CHENG, N. (2022). BIOSENSOR FOR AGRICULTURE AND FOOD SAFETY: RECENT ADVANCES AND FUTURE PERSPECTIVES. *ADVANCED AGROCHEM*, 1(1), 3–6.
[HTTPS://DOI.ORG/10.1016/J.AAC.2022.08.002](https://doi.org/10.1016/j.aac.2022.08.002)

WEI, L.-N., LUO, L., WANG, B.-Z., LEI, H.-T., GUAN, T., SHEN, Y.-D., WANG, H., & XU, Z.-L. (2023). BIOSENSORS FOR DETECTION OF PARALYTIC SHELLFISH TOXINS: RECOGNITION ELEMENTS AND TRANSDUCTION TECHNOLOGIES. *TRENDS IN FOOD SCIENCE & TECHNOLOGY*, 133, 205–218. [HTTPS://DOI.ORG/10.1016/J.TIFS.2023.02.012](https://doi.org/10.1016/j.tifs.2023.02.012)

WILLIAMS, A., AGUILAR, M. R., PATTIYA ARACHCHILLAGE, K. G. G., CHANDRA, S., RANGAN, S., GHOSAL GUPTA, S., & ARTES VIVANCOS, J. M. (2024). BIOSENSORS FOR PUBLIC HEALTH AND ENVIRONMENTAL MONITORING: THE CASE FOR SUSTAINABLE BIOSENSING. *ACS SUSTAINABLE CHEMISTRY & ENGINEERING*, 12(28), 10296–10312.
[HTTPS://DOI.ORG/10.1021/ACSSUSCHEMENG.3C06112](https://doi.org/10.1021/acssuschemeng.3c06112)

WILSON, A. (2017). TECHNO-OPTIMISM AND RATIONAL SUPERSTITION. *TECHNE: RESEARCH IN PHILOSOPHY & TECHNOLOGY*, 21.

WOLF, G. (2016). *THE QUANTIFIED SELF: REVERSE ENGINEERING*.
[HTTPS://DOI.ORG/10.7551/MITPRESS/10293.003.0007](https://doi.org/10.7551/MITPRESS/10293.003.0007)

YÁÑEZ-SEDEÑO, P., AGÜÍ, L., VILLALONGA, R., & PINGARRÓN, J. M. (2014). BIOSENSORS IN FORENSIC ANALYSIS. A REVIEW. *ANALYTICA CHIMICA ACTA*, 823, 1–19. [HTTPS://DOI.ORG/10.1016/J.ACA.2014.03.011](https://doi.org/10.1016/j.aca.2014.03.011)

YÁÑEZ-SEDEÑO, P., AGÜÍ, L., CAMPUZANO, S., & PINGARRÓN, J. M. (2019). WHAT ELECTROCHEMICAL BIOSENSORS CAN DO FOR FORENSIC SCIENCE? UNIQUE FEATURES AND APPLICATIONS. *BIOSENSORS*, 9(4), ARTICLE 4.
[HTTPS://DOI.ORG/10.3390/BIOS9040127](https://doi.org/10.3390/bios9040127)