Innovative Methods for Invasive Mussel Detection

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The goal of this scoping project was to investigate the potential of utilizing innovative methods to detect microscopic invasive dreissenid mussels in the lab and in the field. This investigation focused on scent detection by dogs and sensor technology as well as automated image analysis. The intent of this scoping project was to gather initial information about technologies that have potential, and to develop a future conducting proposal that will allow for further investigation and potentially implementation of new methods that will benefit the Reclamation invasive mussel monitoring and early detection program.

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Executive Summary

The Bureau of Reclamation (Reclamation) Ecological Research Lab is one of the primary labs in the Western United States that analyzes invasive mussel early detection samples. Current early detection methods involve the collection of plankton tow net samples, which are preserved and sent to the lab where they are analyzed under a microscope to detect the larval stage (veliger) of the mussel. If veligers are detected, then quantitative polymerase chain reaction genetic analysis of the veligers is conducted to confirm species identification. Despite the accuracy of microscopy and DNA analysis methods, there are situations where more rapid and/or on-site detection of mussels is required, and there is a need to identify faster and more cost-effective methods of analyzing samples with large numbers of mussels. The lab would also benefit from methods to scan or confirm microscopy results for samples that are difficult to process, including those that contain significant total suspended solids such as phytoplankton, zooplankton, and sediment.

The goal of this scoping project was to investigate the potential of utilizing innovative methods to detect microscopic dreissenid mussels in the lab and possibly in the field. This investigation focused on scent detection by dogs and sensor technology as well as automated image analysis. The intent of this scoping project was to gather initial information about technologies that have potential, and to develop a future conducting proposal that will allow for further investigation and potentially implementation of new methods that will benefit the Reclamation invasive mussel monitoring and early detection program.

Dogs have been used to detect invasive mussels at watercraft inspection stations for many years and several studies have investigated the ability of dogs to detect the microscopic veliger stage of mussels. We reached out to five conservation dog businesses to gather additional information about any research or testing they have conducted or participated in regarding the use of dogs for detection of veligers (or other aquatic invasive species) in laboratory settings. Overall, it appears there have been limited studies investigating the use of dogs in the lab but many of the dog trainers feel that it is possible for dogs to be utilized in this setting in some manner. At this point, it is unclear if dogs would be able to detect mussels in preserved samples as it is unclear if the scent pattern would be disrupted or changed by the alcohol preservative, and this would be the focus of future research. Utilizing dogs to scan samples before or after additional analysis with microscopy and environmental DNA (eDNA) would likely be a possibility and could be cost effective.

Information about the potential to develop scent sensors for the detection of dreissenid mussels was gathered by working with the Reclamation Research and Development Office Prize Competition Program to run a technology search with the contractor, yet2. The scope of the technology search was to identify current and emerging scent detection sensor technologies that could be utilized to detect dreissenid mussel veligers and possibly their eDNA in plankton tow samples that contain other zooplankton, phytoplankton, sediment, lake water, ethanol, and tris buffer. A total of 17 scent detection technologies were identified and of the 17 technologies identified, six were categorized as highly interesting, seven were categorized as interesting, and the other four were either rejected or placed on hold.

A Material Transfer Agreement (MTA) was established with a company in the process of developing an automated sampling device that incorporates machine learning to specifically identify dreissenid mussel veligers. The purpose of the MTA is for Reclamation to send the company water samples containing preserved veligers to determine if the device can accurately detect and enumerate veligers. Unfortunately, the company experienced development delays and has not been ready to receive samples.

A conducting proposal was submitted and funded by the Science and Technology Program in 2022 which will provide funding to continue to pursue additional investigation and potentially research on the technologies identified in this scoping project.

1. Introduction

The early detection and prevention of invasive quagga (*Dreissena rostriformis bugensis*) and zebra (*Dreissena polymorpha*) mussel spread is a priority for the Bureau of Reclamation (Reclamation), the Department of the Interior, and Western states. Invasive mussels pose a significant risk to natural habitats, recreation, and infrastructure like hydropower facilities. The Bureau of Reclamation Ecological Research Lab (Eco Lab) is one of the primary labs in the West that analyzes invasive mussel early detection samples. Current early detection methods involve the collection of plankton tow samples, which are preserved and sent to the lab where they are analyzed under a microscope to detect the larval stage (veliger) of the mussel. If veligers are detected, then quantitative polymerase chain reaction genetic analysis of the veliger is conducted to confirm species identification. The lab also offers environmental DNA (eDNA) analysis where a portion of the water sample is analyzed for quagga or zebra mussel DNA.

Despite the accuracy of microscopy and DNA analysis methods, there are situations where more rapid and/or on-site detection of mussels is required, and there is a need to identify faster and more cost-effective methods of analyzing samples with large numbers of mussels. The lab would also benefit from methods to detect or confirm microscopy results for samples that are difficult to process, including those that contain significant total suspended solids such as phytoplankton, zooplankton, and sediment. There are also situations where more immediate and on-site information about mussel presence is needed, including situations like fish transport, boating, diving, or environmental field sampling. In-situ veliger detection could also be useful as an additional monitoring tool for reservoirs with mussel detections, or to provide continuous monitoring at sites where a treatment was applied for mussel control.

The goal of this scoping project was to investigate the potential of utilizing innovative methods to detect microscopic dreissenid mussels in the lab and possibly in the field. This investigation focused on scent detection by dogs and sensor technology as well as automated image analysis. The intent of this scoping project is to gather initial information about technologies that have potential and to develop a future conducting proposal that will allow for further investigation and potentially implementation of new methods that will benefit the invasive mussel monitoring and early detection program. New methods may improve the ability to detect mussels in a variety of situations and will potentially reduce the costs and time limitations associated with traditional microscopy and DNA analysis.

2. Canine Scent Detection

Canines have highly developed olfactory senses which are up to 100,000 times more sensitive than humans. Detection dogs have been trained to sniff out explosives, drugs, and even cancer in human blood samples. Conservationists have been using detection dogs since the mid-1990s, and dogs are currently used to detect endangered species (bears, owls, wolves, turtles, and bees), invasive species (plants, mammals, reptiles, fish, snails, and mussels), and wildlife diseases (American foulbrood in beehives, avian influenza in waterfowl) (Lowrey, 2020). Several studies have found that conservation detection dogs can increase survey accuracy and decrease survey time (Bryson, 2019; Long et al., 2007, Wasser et al., 2012, Woollett et al., 2014, Orkin et al., 2016). Many dogs trained for conservation detection activities are rescued from shelters and can be trained to detect multiple scents. Dogs that are good candidates for detection work typically have a good temperament around people, are motivated by balls/toys and play, and have high energy and focus (Sawchuk and Hurt, 2018). Dogs can be trained to detect different targets simultaneously and Ying (2020) demonstrated that dogs can be retrained to detect new targets and reject previous targets.

The benefits of utilizing dogs for detection includes their ability to cover large areas very quickly, their ability to locate difficult to find species, and their identification speed, especially compared to more traditional methods that require specialized personnel and instruments (Becker et al., 2017; Dahlgren et al., 2012; Duggan et al., 2011; Powlesland et al., 1995; Van De Werfhorst et al., 2014). However, the training of qualified scent detection dogs can be expensive and time consuming (Duggan et al., 2011; Gsell et al., 2010; Long et al., 2007; Robertson & Fraser, 2009). Another issue often encountered is that dogs can potentially cue off their handlers, leading to false detections or confusion (Browne et al., 2015; Edwards, 2019; Lit et al., 2011).

Dogs have been used to detect invasive mussels at watercraft inspection stations for many years. A trial conducted in Alberta, Canada to compare the accuracy and efficacy of trained canine handler-teams versus trained watercraft inspectors at detecting mussel-fouled boats found that dogs correctly assessed 100% of fouled watercraft, and the humans 75% (Sawchuk and Hurt 2018). It takes approximately 6 weeks to train dogs to detect zebra and quagga mussels. Dogs are trained to detect the scent of mussels and they notify the presence of mussels by sitting. Typically, dogs can work 45 minutes at a time followed by a 15-minute break, but the total amount of time they can work each day depends on factors such as temperature and weather conditions (Gagliardi, 2020). For example, Barnacle (a dog trained by Mussel Dogs) was able to inspect a single boat in 10-15 seconds, and he inspected 110 boats in one day at a Wyoming check station (Gagliardi, 2020). This was a higher than the usual number of inspections, which was made possible by the cooler weather.

Several studies have investigated the ability of dogs to detect the microscopic veliger stage of mussels. DeShon et al. (2016) tested the ability of four dogs that had previously been trained to detect quagga mussel adults to detect veligers without extra training. They also investigated if extra training with veligers would result in canines being imprinted with veliger scent and attempted to determine the lowest veliger concentration that the dogs could detect. After initial testing, the handlers found the dogs needed to do additional imprint training with the veliger odor starting at a higher concentration of veligers (2,088 veligers). Within three days, the dogs recognized the veliger odor and were able to respond accurately as the veliger concentration was reduced by 50%. The dogs were able to discriminate veliger samples at a low threshold of odor despite at times becoming frustrated and bored with the study. Dogs were able to accurately detect samples containing as low as 31 veligers.

Another proof of concept study was conducted in 2017 to investigate the ability of dogs to detect veligers in lake water samples (Sawchuk and Hurt, 2018). Seven trained dogs were tested with water samples from eight reservoirs in Texas. The dogs were presented with six 5-gallon buckets that contained 12 liters (L) of water and from 0-68 veligers per L, as well as other zooplankton and algae collected from the lake. The dogs performed over 3,200 bucket checks. Overall, the dogs accurately identified buckets containing veligers 80% of the time and were able to detect settled juvenile mussels 100% of the time. The authors of the study suggest that a practical application for the use of dogs might be pre-screening of early detection and monitoring samples (Sawchuk and Hurt, 2018). This pre-screening might allow for samples that are found to contain mussel scent to be prioritized in the lab ahead of other samples. The authors do suggest that additional studies would need to be conducted to determine how to use dogs for this laboratory application. The authors also suggest that it would be important to employ dogs that are well suited to the task, as dogs can display different levels of proficiency when it comes to search types/ methods.

A recent study by Texas Tech University (unpublished personal communication) investigated the ability of dogs to detect veligers in the lab and compared their detection ability to eDNA detection. The researchers were particularly interested to learn the strengths and weaknesses of each method and the limits of detection. The results of this study indicate that trained dogs can detect very low concentrations of veligers and that not all dogs were able to perform at the same level. Although eDNA analysis was more accurate, dogs do provide other benefits such as real-time detection.

The ability of dogs to detect invasive species in preserved samples has rarely been studied. One study by Denby (2021) determined that dogs were able to accurately detect brown bullhead catfish (*Ameiurus nebulosus*) in water samples that were preserved by refrigeration or freezing for up to one week. Matthew et al. (2021) investigated the effects of preserving (refrigeration and freezing) giant bullfrog (*Pyxicephalus adspersus*) scent for up to six months and found that detection sensitivity was negatively correlated with scent preservation time.

Currently there are no consistent measures for reporting of scent-dog performance (Bennett et al., 2019). Bennett et al. (2019) suggests comprehensive evaluation for the use of conservation detection dogs should include five aspects: precision, sensitivity, effort, cost, and comparison with other methods. They recommend quantitative measurement of precision, sensitivity, and effort, which can be used to measure performance with a confusion matrix. In this context, precision is the proportion of all alerts directed toward a true target. Precision measurements are most important for situations like microscopic veliger detection where dogs are detecting scent from visually indistinguishable samples. Sensitivity is the proportion of targets found relative to the total number of targets available. Effort is the time spent searching a unit of area. It is also important to consider the cost and return on investment of implementing dogs as well as comparing the dogs with other survey tools. It is possible that for some situations, dogs might require a greater total financial investment, but they have a higher probability of detection than other methods (Bennett et al., 2019).

Bennett et al. (2019) also conducted a literature review and identified 61 studies that reported quantitative information on the performance and cost of detection dogs working on conservation projects. Very few studies reported on precision, sensitivity, and efficiency simultaneously and there were large variations in the ranges, but most studies demonstrated high performance. Only 17 studies reported on the cost. The studies identified in this literature review were focused on field detection and not detection of species in samples in a laboratory setting, indicating that additional research is needed.

We reached out to the following list of conservation dog businesses to gather additional information about any research or testing they have conducted or participated in regarding the use of dogs for detection of veligers (or other aquatic invasive species) in laboratory settings.

- Conservation Dogs Collective
- Mussel Dogs
- Midwest Conservation Dogs
- Nose No Limit
- Working Dogs 4 Conservation

Overall, it appears there have been limited studies investigating the use of dogs in the lab but many of the trainers feel that it is possible for dogs to be utilized in this setting in some manner. Utilizing dogs to scan samples before or after additional analysis with microscopy and eDNA would likely be a possibility and could be cost effective. One trainer indicated that the use of dogs in the lab could provide a major cost savings, as each dog costs approximately $1,500 to train, and once trained, they cost approximately $450 per day to analyze between 50-100 samples. Initial studies have found that dogs do better at detecting veligers in concentrated samples like plankton tow net samples rather than surface grab samples. Trained dogs should not have any issues dealing with samples that have heavy loads of concentrated zooplankton or algae as they are able to easily distinguish veligers from other sample contents. At this point, it is unclear if dogs would be able to detect mussels in preserved samples as it is unclear if the scent pattern would be disrupted or changed by the alcohol. There were differing opinions about if it would be harmful for dogs to regularly sniff samples containing ethanol, but it is something that should be further investigated.

3. Scent Detection Sensor Technology

While canine scent detection is a potential option for laboratory use, there are still some limitations. The development of scent detection sensors could prove to be as effective or more effective as dogs while providing additional benefits. To gather information about the potential to develop scent sensors for the detection of dreissenid mussels, we worked with the Reclamation Research and Development Office Prize Competition Program to run a technology search with the contractor, yet2. Conducting a technology search with assistance from experts allowed more complete identification of existing and experimental technologies and prioritization of the technologies identified to better establish next steps.

The scope of the technology search was to identify current and emerging scent detection sensor technologies that could be utilized to detect dreissenid mussel veligers and possibly their eDNA in plankton tow samples that contain other zooplankton, phytoplankton, sediment, lake water, ethanol, and tris buffer. There is additional interest in applying the sensors to detect mussels and other invasive species through the air or water on watercraft and in their enclosed compartments. The following list of capabilities, specifications, and information we were seeking was provided to the contractor to direct the search.

Sensor capabilities:

- Sensitivity: discern individual animal and plant species; required concentration of species material vs total sample volume; ability to detect eDNA; detection sensitivity in samples containing interferences such as concentrated zooplankton, and phytoplankton, bacteria, and ethanol.

- Medium: air or water; water mixed with ethanol; field vs lab conditions; ability for detection inside of difficult to access compartments on boats such as ballast tanks, engines, bilges etc.
- Metrics: accuracy; precision; bias.

Handheld devices:

- Cost: cost of instrument; cost per sample; maintenance costs.
- Maintenance: calibration frequency; type of calibration procedure (on-site or send to manufacturer); other maintenance requirements.
- Ease of use: number of steps required for analysis; analysis time; training requirements.

The Reclamation team met with the yet2 team to clarify scope and was briefed every few weeks on findings. They conducted a global search of handheld and portable electronic sensors across various applications, including chemical detection of air quality, hazardous materials, biosecurity, odors to determine food quality and taste improvement, and disease detection through breath-based biomarkers, etc. They organized findings by sensor type, developed a prioritization chart based on ranking criteria, and created a table highlighting the strengths and weaknesses of each technology.

A total of 17 scent detection technologies were identified, which fell into the following list of sensor categories (followed by the number of technologies identified in each category).

- Gas chromatography (2)
- Photoionization detector (subset of gas chromatography) (2)
- Mass spectrometry (1)
- Mach-Zehnfer interferometer (1)
- Nanomaterials (5)
- Metal oxide (2)
- Protein receptors (1)
- Combination of categories or other (3)

Of the 17 technologies identified, six were categorized as highly interesting, seven were categorized as interesting, and the other four were either rejected or placed on hold. The ranking criteria used to create the prioritization/comparison chart included the following.

- Likelihood of veliger detection
- Price
- Battery life
- Sensitivity
- Technology readiness level
- Intellectual property standing
- Weight and dimensions
- Self-learning
- Sensor type

To assess the potential likelihood of veliger detection of the different sensor categories for invasive mussel detection, yet2 provided a sensor comparison matrix (Appendix A). Of the nine categories assessed, yet2 determined that the technologies with the most potential for veliger detection were in the categories of quartz crystal microbalance, gas chromatography/mass spectrometry, optical Mach-Zehnfer interferometer, and biological odorant related proteins.

Identifying dreissenid mussel-specific volatile organic compounds (VOCs) may be required to train existing methods, or to develop new methods. VOCs specific to dreissenid mussels have not yet been identified. yet2 interviewed Dr. Nick Tuckey of the New Zealand Institute for Plant and Food Research Ltd, in Nelson, New Zealand. Dr. Tuckey has experience identifying VOCs from Greenshell™ mussels (Tucky et al., 2012). Dr. Tuckey was able to isolate some compounds but indicated that it is very difficult to identify compounds that are specific enough to identify a particular mussel species. He also found that the compounds tend to be influenced by what the mussels eat, which can differ based on season and waterbody. It is possible that this could be a limitation in training existing and developing new technologies.

4. Automated Image Analysis

The Eco Lab has also been investigating the potential for automated image analysis to be utilized for select samples. Monitoring samples that contain large numbers of veligers require a lot of time for analysis, and the use of an automated sampling system would have the potential to significantly reduce the amount of time it takes to analyze those samples, allowing lab staff to focus on early detection sample analysis. There are several automated sampling devices available on the market that are designed to monitor zooplankton and macroinvertebrates. Reclamation previously ran a prize challenge to identify such devices; however, most of the devices are designed to monitor populations in-situ and not in the lab and have not been designed specifically to detect veligers.

In a past effort funded by the Science and Technology Program, the Eco Lab worked directly with FlowCam to develop a system specifically designed for veliger analysis in the lab. The Mussel FlowCam was able to accurately detect veligers, but the requirement of filtering the sample before analysis resulted in loss of veligers and sample processing time was not greatly improved. The FlowCam had an extremely small flow cell that limited the speed of sample processing and the size of particles that passed through the cell. This method was not robust enough to handle regular sample processing.

More recently, the Eco Lab established a Material Transfer Agreement (MTA) with a company working to develop another automated sampling device that incorporates machine learning to specifically identify dreissenid mussel veligers. A MTA was pursued because the prototype device was able to be utilized both in-situ and in the lab and was able to process samples quickly and without filtration. Since the establishment of the initial MTA in 2020, the company has run into some setbacks with development stemming from the pandemic and disruption in the supply chain. They have made progress with training the device and are working with a university and the United States Geological Survey (USGS) to do some in-situ testing with zebra mussel veligers in Minnesota.

The purpose of the MTA is for Reclamation to send the company water samples containing preserved veligers to determine if the device can accurately detect and enumerate veligers. Unfortunately, with the delays, the company has not been ready to receive samples and is still working on development and machine learning training. Reclamation has sent the company a single sample containing many veligers that can be used for training the device.

5. Next Steps

5.1 Canine Scent Detection

The use of dogs to scan samples in the lab does appear to be a promising area of study that should be further investigated. A conducting proposal to support the continuation of this research was funded by the Science and Technology Program in 2022. One of the dog trainers we contacted was interested in the research and potentially working with the Eco Lab to conduct some studies focused on the impacts of ethanol on detection and determining the lowest numbers of veligers that different dogs can detect.

5.2 Scent Detection Sensor Technologies

Although scent detection sensor technologies do appear to have potential, this would be a completely new application and a lot of work would need to be done to develop the technology. The first step will be to reach out to the companies to gather more information on if they think their technology would be capable of detecting dreissenid mussel veligers in plankton tow samples or on boats. If they think it is a possibility, it will be important to learn how to move forward with developing the technology and how Reclamation would be involved. It will be important to learn how each technology would need to be trained to detect mussel scent. It may be possible to train using adult mussels or it may be important to first identify the species-specific VOCs by gas-chromatography mass-spectrometry. Limitations on moving forward with this effort might include unfeasible cost or inability of technologies to detect single veligers, especially in samples containing interferences such as other zooplankton and phytoplankton and ethanol.

We plan to continue working with yet2 to set up introductory calls with the companies that have the most promising technologies. We plan to discuss the following questions with the companies to determine if it is possible to move forward with development of the sensors.

- Is it possible to utilize the technology for veliger detection?
- How well would the technology work on complex samples containing other zooplankton, phytoplankton, ethanol, and tris buffer?
- What would development look like for teachable sensors or custom development?
- What is the estimated cost of development?
- Is there interest in working with Reclamation, and how would Reclamation be involved in development?

- What would be the estimated cost to purchase the technology after development?
- What is the timeline of development to deployment?
- Could the technology be customized for use on other invasive species or algal toxins?
- What limitations exist?

A conducting proposal was submitted and funded in 2022 that will partially support continuation of this effort, and additional funding was requested through Reclamation's Policy Office.

5.3 Automated Image Analysis

Automated image analysis and machine learning is a quickly developing field of study which has a lot of potential for this application. Reclamation will continue to work with the company with which we hold an MTA to assess their technology. Funding for this effort has been secured through a 2022 Science and Technology Program conducting proposal.

5.4 Project Data

- Share Drive folder name and path where data are stored: \\bor\do\TSC\Jobs\DO_NonFeature\Science and Technology\2021-PRG-New Methods for Mussel Detection
- Point of contact: Sherri Pucherelli. spucherelli@usbr.gov, 303-445-2015
- Data description: Final report, referenced literature, and technology search results

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Appendix A

Sensor comparison matrix prepared by yet2 utilizing the reference [Artificial Olfaction in the 21st Century]

	Indeterminate Gas Sensor	Discrete Gas Sensors				Physical Gas Sensors			Biologic
Technology	Photoionization Detector (PID)	Chemoresistive Metal-Oxide (MOX)	Conducting Polymers (CP)	Quartz Crystal Microbalances (QCM)	Nanomaterials	Ion Mobility Spectrometers (IMS)	Gas Chromatography - mass spectrometry (GC-MS)	Optical (Mach-Zehnder Interferometer)	Biologic Odorant Related Proteins
yet2 Assessment of Suitability	Poor	Fair	Fair	Good	Fair	Fair	Good	Good	Good
How it works	Uses ultraviolet light to identify VOCs. Each VOC has a ionization potential (IP) which is the amount of energy required to liberate an electron.	Uses a delicate film to detect compounds in the surrounding atmosphere, such as benzene, ethanol, and toluene.	Transforms analytes to detectable physical signals such as current, absorbance, mass or an acoustic variable.	Detects change in mass or thickness of layers adhering to the surface of a quartz crystal. Can be modified with various types of coatings to optimize sensitivity and selectivity of gas absorption. Often combined with MOX or CP as layers.	Enable sensors to detect very small amounts of chemical vapors. Nanomaterials include graphene, metal nanoparticles (Ag or Au) and polymer,	Packets of analyte ions travel through a gas-filled “drift tube” under the influence of a uniform electric field and their arrival time is recorded at a detector.	Works on the principle that a mixture will separate into individual substances when heated. The heated gases are carried through a column with an inert gas (such as helium). As the separated substances emerge from the column opening, they flow into the MS for detection	Surface plasmon resonance using sensors, an optical light source and a detector which measures the absorbance of an odor onto a metallic, metal oxide or nanomaterial molecule which is deposited onto a gold coated prism. Odors are analyzed as image.	Odorant-associated proteins have been incorporated into biosensors
Pros	low cost, fast response time, small size	cheap, fairly common, been in the market for over 10 years	high sensitivity, short response time, operate at room temperatures, easy fabrication due to good mechanical properties	very senstive, inexpensive, portable, fast response times, low cost, simple structure	high diversity, high sensitivity, small form factor	more stability and repeatability, less prone to drift compared with chemical reactions, incredible sensitivity (ppt for some chemical families)	most common for detection and quantification of VOCs	sensitivity to a wide range of odors, captures odor signatures, lightweight, low power, small size	Extremely stable to high temperature, Small size hence makes portable devices
Cons	Provide nonselective measurement, e.g. measures gas concentration without identifying the gas itself. UV lamp IP value (10.0 eV, 10.6 eV or 11.0 eV) most be selected based on the VOC molecules to be detected. Chemicals with high ionization energies (< 11.7 eV) such as methane or carbon tetrachloride can not be detected.	high power consumption (>100mW), high temperature operation (>150oC), badly effected by humidity and long-term drift	limited lifetime, not reuseable, unable to detect VOCs that are not reactive at room temperature, such as benzene, toluene.	Viscoelasstic - have a strain rate dependent on time. Did not find any eNose devices using this currently.	challenges with repeatability, reliability	not tolerant to higher humidity levels, requires high voltages	not capable of directly analyzing substances that are nonvolatile, polar, or thermally labile	it requires frequent calibrations for preciseness	affected by aromatic compounds, that can efficiently quench the signal by direct electron transfer
Primary Use cases	Detection of highly volatile compounds	Food, air & breath analysis	Detection of Gas Leaks	Fruit freshness	Distinguish the mixtures of gases, volatile organic compounds	Detection of several types of drug residues or traces of harmful chemicals in a variety of food	Screening tests for the detection of several congenital metabolic diseases	Gaseous compounds	Odor and Chemicals Detection
Sensor Drift	No, but false positives at high humidity	Yes	Yes	Yes	Yes	Minor	Minor	Minor	TBD
Relative Cost	Low	Low	Low	Low	Low	Medium	Medium	High	TBD
Sensitivity	High	Average	Low	High	High	High	High	Average	High
Relative Maturity	Established	Mature	Established	Established	Nascent	Mature	Mature	Nascent	Nascent
	1990s	1960s	1980s	1980s	2010s	1950s	1950s	2010s	2020s