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Market Perspectives and Future Fields of Application of Odor Detection Biosensors—A Systematic Analysis †

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† Presented at the 1st International Electronic Conference on Biosensors, 2-17 November 2020; Available online: https://iecb2020.sciforum.net/.

Received: 15 October 2020; Accepted: date; Published: date

Abstract: The technological advantages that biosensors have over conventional technical sensors for odor detection have not yet been comprehensively analyzed. However, these are necessary for assessing its suitability for specific fields of application as well as its improvement and development goals. In this paper specific market potentials of biosensors for odor detection are identified by applying a tailored methodology that enables the derivation and systematic comparison of both performance profiles of biosensors as well as requirement profiles for various application fields. Therefore, the fulfillment of defined requirements is evaluated for biosensors by means of 16 selected technical criteria in order to determine a specific performance profile. Further, a selection of application fields for odor detection sensors is derived to compare the importance of the criteria for each of the fields, leading to market specific requirement profiles. The analysis reveals that the requirement criteria considered to be the most important ones across all application fields are high specificity, high selectivity, high repeat accuracy, high resolution, high accuracy and high sensitivity. All these criteria except for the repeat accuracy can be potentially better met by biosensors than by technical sensors, according to the results obtained. Therefore, biosensor technology in general has a high application potential for all the areas of application under consideration. Especially health and safety applications are considered to be applications with high application potential for biosensors due to the high correspondence between requirement and performance profiles.

Keywords: odor sensor; market analysis; technology assessment; application field; performance profile; requirement profile

1. Introduction

Research has been conducted on odor sensors since the 1980s [1]. Over the years, different methods and technologies have been developed. However, all these technologies have serious disadvantages, namely, low specificity and sensitivity which have prevented a breakthrough of odor sensors until now [2]. Biosensors appear to be the appropriate technology to help odor sensors to a final breakthrough [3]. New developments in biotechnology make it possible to develop odor sensors that are able to identify gases and volatile organic compounds (VOCs) in comparatively low concentrations. Due to their specific properties, these new technologies manage to open up new application possibilities. These include, for example, new forms of cancer diagnosis or reliable testing of food quality [1 At this stage it is essential to to specify these application possibilities at an early stage in order to enable a more targeted market entry. To this date a comprehensive analysis of the requirements for application fields of odor detection sensors has not been presented as well as a meta-analysis showing the specific advantages of biosensors in this context. This paper thus addresses the following research questions:

1. What are the specific market potentials of odor detection biosensors?
2. What are therefore the most promising application fields for odor detection biosensors?

In this paper, an evaluation method is presented, which is used to develop requirement profiles for different application areas and performance profiles for bio-based odor sensor technologies. By comparing the performance and requirement profiles, these questions can be answered and fundamental statements about application-specific market potentials for biosensors can be made.

2. Basics

The following section gives a short overview of the different odor sensor technologies and their classifications. Furthermore, the technical criteria used to create the performance profile are briefly described. At the end of this section, potential markets and applications for odor sensors are discussed.

2.1. Types of Odor Sensing Technologies

Figure 1 illustrates a classification sheme develepod in accordance with [3–7]. A distinction can be made between biosensors and technical sensors. Biosensors contain integrated biological elements, such as cells, cell tissue, proteins or nanovesicles which are fundamental for their functionality. Technical sensors consist exclusively of technical components and can be divided into so-called electronic noses and conventional instrumental analysis. In the following, these technologies are briefly described.

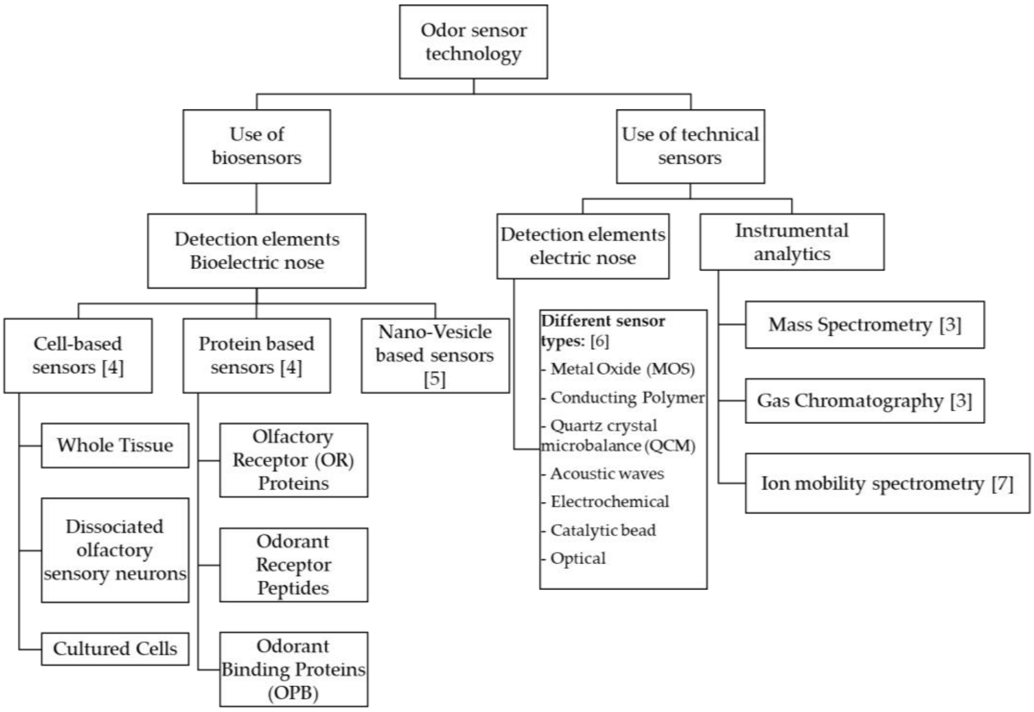

Figure 1. Overview of different technologies for odor detection. Own presentation, based on [3–7].

An electronic nose is a technical system consisting of various chemical sensors (usually so-called CMOS (Complementary metal-oxide-semiconductor) sensors) that are connected to form a sensor array. Metal oxide and polymer sensors are the most commonly used types of sensors. These sensors can convert the chemical information into an analytical signal. The result of a measurement is a complex signal pattern. This pattern has to be compared with a reference pattern which was derived primarily from previous knowledge acquired from an existing data set. Only by matching the signal pattern with the reference pattern, a result with analytical significance is obtained [8].

Biosensors and biosensors, instead of conventional sensors, use bio-elements such as proteins, nanovesicles, cell tissue or entire individual cells as recognition elements. In a biosensor, the analyte to be measured docks to a bioreceptor. This creates a specific compound leading to a biochemical reaction that can be technically recorded and evaluated. For example, the reaction may involve a change in the thickness of the bioreceptor layer, the refractive index, light absorption or electrical charge. These changes are detected by means of a transducer and converted into a signal, which is usually amplified and processed by an electronic system. Thus, a specific signal is generated for each specific substance [9].

Conventional analytical methods include, for example, gas chromatography and mass spectrometry. Here the mixtures of substances in liquid or gaseous state are examined for their chemical composition using different physical measuring principles such as the detection of mass-to-charge ratio in mass spectrometry or polarity as in gas chromatography [3].

2.2. Technical Performance Criteria of Odor Sensing Technologies

In order to describe the performance of an odor sensor, both static parameters, such as selectivity and sensitivity, and dynamic parameters, such as service life, can be considered. In the following, the individual criteria considered in this paper are described. The selection and definitions were developed in the course of an expert workshop of the authors based on Fraden et al. 2016 and verified by the review and supplementation of external experts in different fields of sensor technology [10].

- **Sensitivity:** Describes the degree to which the output signal (measured value) changes in relation to the change of the input signal (measuring signal)
- **Accuracy:** Describes the maximum deviation of the sensor’s measurement value from the real (ideal) value
- **Selectivity:** Describes the response of the sensor to a certain group of analytes or one specific analyte
- **Specificity:** Indicates the probability that the measured value is falsely positive or falsely negative
- **Resolution:** Describes the smallest measurable change the sensor is able to register
- Repeatability: Indicates the error that occurs with repeated measurements, under the same initial situation
- **Lifetime:** Describes the period of time during which the sensor remains functional
- **Reliability:** Describes the performance of the sensor which must be maintained over a defined period
- **Resistance to environmental influences or stability:** Describes the accuracy of the measurement results in case of changing environmental influences, such as temperature, humidity, radiation or magnetism
- **Maintenance effort:** Describes the overall effort of measures that keep the system in a functional state
- **Multi-sensing capability:** Describes the ability to measure several different substances in parallel
- **Cost:** Describes the monetary costs of the manufacturing process for materials and the production process
- **Dimensions:** Describes the flexibility of relevant, characteristic geometric dimensions of the sensor shape
- **Weight:** Mass of the body in kg per measuring unit or sensor
- **Operability:** Describes the simplicity of use
- **Measurement duration:** The time required to complete a measurement process

2.3. Markets and Application Fields for Biosensors

The annual turnover of all suppliers in the biosensor market was $11.5 billion in 2014 and is expected to grow to $28.78 billion by 2021. This corresponds to a growth rate of 12.2% per year [11]. In the following, the fields of application for the use of odor sensors are listed and described regarding their market volumes.

- **Healthcare:** The healthcare market includes the ambulatory and stationary achievement contribution by established physicians and dentists, hospitals as well as other service providers [12]. In 2019, the health care system in Germany had a turnover of €86.5 billion [13]. In 2018, 48,346 companies in Germany were active in the healthcare sector [14]. One example of a future field of application is diagnostics. Sick people excrete different VOCs compared to healthy people. These VOCs are used as biomarkers and can be identified by breath, urine and other body fluids. A diagnosis based solely on a patient’s odor requires very accurate diagnostic equipment [15]. Odor sensors prove to be a suitable diagnostic tool when it comes to diagnosing diseases. There is a great demand for non-invasive diagnostic methods in the healthcare sector. These sensor devices should be able to perform real-time monitoring, they should be portable and inexpensive [16].
- **Food industry:** Food industry comprises food and feed manufacturers together with beverage industry. Altogether, there are about 6000 companies with more than 20 employees in German food industry [17]. In 2018, these companies employed more than half a million people. With an annual turnover of almost with a revenue of €180 billion, the food industry is one of the largest industries in Germany [18]. The odor sensors in this industry should enable fast detection of quality changes during production. During quality control, impurities and pathogens are identified. Furthermore, the correct composition of the produced food and its smell and taste can be analyzed [19].
- **Agriculture:** Agriculture is the economic activity where soil, livestock, labor and know-how produce agricultural products that ensure the supply of plant and animal food to the people [20]. In 2018, there were 266.600 active companies in Germany [21]. They had a turnover of €38.3 billion, in 2018 [22]. Odor sensors can be used in agriculture to determine the quality of products and stocks based on odors or VOCs, or to detect pests and other negative influences already in the field [3].
- **Cosmetics industry:** Cosmetics include all products that have a caring effect but are also used for beauty care. The industry is mainly determined by the large consumer goods groups. In 2018, there were 137 Companies in the German industry for the production of cosmetics [23], generating sales of approx. €6.4 billion [24]. Fields of application for odor sensors in the cosmetics industry are mainly quality control of production goods. Odor sensors can also be used in production to check the correct composition of the products, in order to be able to analyze odors and develop them more specifically for example [3].
- **Safety applications:** Safety applications are all applications that aim to detect hazardous substances. Smells contain important information about the environment and activities relevant to military and safety-oriented applications. This includes the detection of explosive materials or hazardous chemicals. However, an odor sensor can also be used for crime prevention tasks, such as security checks at airports or drug detection [25]. In 2021, the security industry in Germany is forecast to generate sales of 9.2 billion euros [26].
- **Environmental monitoring:** In environmental monitoring, indoor and outdoor air is analyzed, in order to detect air quality issues by harmful VOCs. These issues occur, for example, during the manufacturing of furniture [27]. The detection of harmful and toxic substances is also one of the areas of application for odor sensors. Furthermore, air quality and factory emissions can be monitored as well as the quality of ground and surface water. Due to the increased environmental awareness and pollution, the market for technological solutions for environmental monitoring applications is growing [19]. The turnover of the German environmental protection industry in 2018 amounted to 71 billion euros [28].

2. Methodology

In each field of application (see Section 2.3) for odor detection sensors, there are different requirements for the technology used, which can be reflected in assessments of technical performance criteria. 16 technical performance criteria (see Section 2.2), that can be used especially for the description of the requirements of odor detection applications, were established within this study through expert workshops and literature research. In order to specifically assess the importance of these criteria for the fields of application, a comprehensive expert survey was conducted with eleven experts from renowned research institutes and companies active in the fields of olfactory sensing electronic noses. Each of the participating experts has extensive experience in research and development of odor sensors. The quality of the survey is, therefore, ensured by the targeted selection of experts who are able to classify the complex relationships between product characteristics and their respective importance in the application fields and markets. The experts were asked to answer the question, which criteria are more or less important for each application field. For this purpose a scoring model was introduced to quantify the qualitative estimates for visualization as follows: 0 = not important, 1 = rather unimportant 2 = important, 3 = very important. In summary, the results of this survey are visualized in specific requirement profiles for each of the fields of application considered, by forming the mean values of the scoring points. Additionally, all individual criteria were assigned into three related classes or categories. The first category combines all criteria related to measurement quality. This includes the resolution and sensitivity of the sensors. The second category includes the handling and the operability of the sensors. For example measuring duration, maintenance effort and multi-sensing-capability are assigned in this category. The third category combines production parameters such as manufacturing costs, weight, durability and dimensions.

Similarly, a performance profile can be drawn up for individual technologies, showing the degree to which the performance criteria are fulfilled by the respective technology. The performance profile for bioelectronics noses was derived to enable statements about the fulfilments of the criteria in order to compare them to the competing technologies of technical sensor, as shown in Figure 1. To evaluate the performance of biosensors in comparison to biosensors and instrumental analysis numerous existing studies and research results were analyzed in a comprehensive meta-analysis regarding the performance perspectives of biosensors in comparison to those competing technologies. For the evaluation, the properties of biosensors are rated with the scale, 0 = is fulfilled worse by comparison; 1 = is fulfilled equally well or no clear statement can be made; 2 = is fulfilled comparatively better.

In Conclusion, by comparing the performance criteria with the requirement criteria, conclusions can be drawn about specific market potentials for the individual fields of application.

3. Results

In the following subsections, the generated performance profile for biosensors (3.1) and the requirement profiles of different application fields (3.2) are presented.

3.1. Performance Profile of Biosensors for Odor Detection

The evaluation results show the performance of biosensors in comparison to technical sensors (electronic noses or instrumental analytics). All references and statements are summarized in Table 1 and the performance profile is graphically illustrated in Figure 2.

Table 1. Evaluation of the fulfilments of performance criteria by bioelectric odor sensors; fields; 0 = is fulfilled worse by comparison; 1 = is fulfilled equally well or no clear statement to be made; 2 = is fulfilled comparatively better.

Properties	Fulfilment	Rating	References
High sensitivity	Due to the natural binding of olfactory receptors (OR) with the specific ligand, the sensor can react even to very small amounts of analyte.	2	[1,29,30,31]
High accuracy	High accuracy due to natural binding of OR with specific ligand.	2	[1,29]

High resolution	Substances can be detected in very high resolutions at a level of nanomoles (or lower)	2	[1,32,33,34]
High repeat accuracy	Currently there are still problems with the stability of the results. No high repeat accuracy can be guaranteed yet.	0	[32,35,36]
High selectivity	It can be tested very specifically for certain substances.	2	[1,3,30,31]
High specificity	Good results for falsely positive and falsely negative measurements.	2	[1,3]
Low weight	A compact and light design for biosensors in comparison to analytical instruments allows online monitoring. Portable devices (sensors on chip) are currently in testing phases. No advantages. Probably no significant advantages over electronic noses to be expected.	1	[19,31]
Small dimensions	Analytical instruments are large benchtop systems permanently installed in laboratories. There are electric noses with a diameter of a few cm. The same is possible for biosensors. Probably no significant advantages over electronic noses to be expected.	1	[31,35]
Low cost	The manufacturing costs for biological odor sensors are not yet finally known. Due to high research and development costs and complex production processes, a high sales price can be expected. For comparison, analytical instruments can cost up to $30,000. Electronic noses are available from $200.	1	[2,4,31,32,37]
High durability	Sensors, which use cells as bioreceptors, currently have a lifetime of just about a few weeks. The durability of these systems, especially for use as industrial sensors, are not reported.	0	[1,3,30,32,37]
Low maintenance effort	Bioreceptors must be replaced regularly. Replacement Receptors must be stored correctly.	0	[4,32,38]
Short measuring duration	Measuring times for biosensors are reported from 5-30 s. Total measuring process takes 5 min. due to sample preparation and pauses between measurements. This is comparatively faster than analytical instruments but in the same range than electronic noses.	1	[1,4,31]
Operability	Usability cannot be conclusively evaluated yet. However, odor sensors allow a non-invasive measuring method that does not require the extraction of sample material.	1	[31,39,40]
Resistant to environmental influences	Sensors must be protected against environmental influences. Susceptible to humidity and temperature fluctuations	0	[3]
Multi-Sensing capability	Biosensors are able to measure several different substances simultaneously.	2	[29,30,40]

As illustrated in Figure 2, biosensors have advantages in terms of sensitivity, selectivity, specificity, accuracy and resolution. This is due to physical bindings of the olfactory receptors with specific ligands. Therefore, the sensor can react even to very small amounts of analyt or even single molecules within gas mixtures [29]. There are also advantages in terms of weight and dimensions. The design of biosensors can be smaller than most technical analysis devices such as mass spectrometers [19].

Disadvantages compared to technical sensors can be seen in terms of durability, maintenance effort, repeat accuracy and resistance to environmental influences. The main reason for this is the limited lifetime and fragility of the used biomolecules. Users are forced to change the biomolecules after a certain time. This is an enormous maintenance effort, which many users are not prepared to bear. Furthermore, the low resistance to environmental influences such as humidity, radioactive radiation or high temperatures is a problem of biosensors, which limits the application possibilities. All biosensors used for example for medical applications must meet the demanding and specific requirements of the medical industry. In addition, improvements and developments of other medical devices create further competitors for biological sensors [11]. A further disadvantage compared to technical sensors are costs. The long development cycles of biological sensors, which can only adapt to the new competitors with difficulty, play a key role here according to the biosensor manufacturer Koniku inc. Regarding the operability and the measuring duration there are neither advantages nor disadvantages for biosensors to be clearly defined.

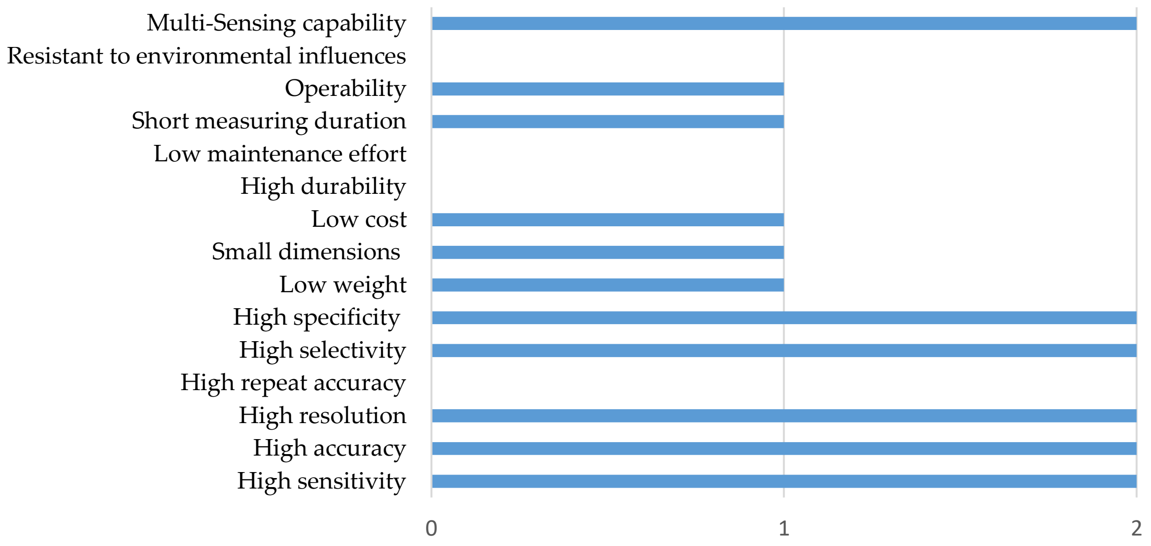

Figure 2. Performance profile of biosensors for odor detection in comparison to competitive technical odor sensors, based on Table 1; fields; 0 = is fulfilled worse by comparison; 1 = is fulfilled equally well or no clear statement to be made; 2 = is fulfilled comparatively better.

3.2. Requirement Profiles for Different Application Fields of Odor Sensing Technologies

In order to derive application specific requirement profiles, each defined requirement criterion was evaluated with regard to its importance for a successful product in the respective fields of application. The evaluation was carried out in a survey leading to the results shown in Figure 3, assigned into three related categories. The first category (a) combines all criteria related to measurement quality. The second category (b) includes the handling and the operability of the sensors and the third category (c) combines production parameters. The following sections describe the results grouped by these categories.

In Figure 3a criteria are shown concerning the measuring quality of odor sensors. Overall, all the measurement quality criteria shown were assessed as "important" or "very important" across all application fields. In comparison of the application fields, it can be seen that all quality criteria shown are of even higher importance for the application fields in the healthcare market and for safety applications compared to the other fields. According to the experts, all quality related criteria shown in Figure 3 are very important for this fields of application. Since safety-critical and sometimes vital data is to be collected in these industries, high measurement quality is essential. For example, for the detection of explosives and medical diagnostics which are considered new fields of application for odor sensors [25] it must be possible to detect even small trace elements and individual molecules with high specifity, sensitivity, accuracy, resolution and selectivity. For safety applications, all criteria were rated 3, thus, as "very important". The only exception for healthcare applications is high resolution which was rated 2.75. High resolution is very important for all other fields of application with a rating of 2.75 as well, except agriculture. However, with a rating of 2.5, the criterion is still considered very important for agricultural applications.

In the category of handling and operation shown in Figure 3b there are stronger differences in the importance ratings for the considered fields of application compared to the criteria of measurement quality shown in Figure 3a. It is illustrated that short measuring times are very important for the food industry, due to the tendency of high throughputs of units to be measured coupled to large production numbers in this field of application. Due to the high risk of time delays, short measurement times are also very important for safety applications. According to the survey, the multi-sensing capability is particularly interesting and rated as important for the food industry, where taste analyses are performed. Tastes are usually defined by compositions of a large number of individual odorous substances. The multi-sensing capability was also evaluated as important for the cosmetics industry, since the composition of many different flavors is also relevant for fragrances.

The resistance to environmental influences is very important for applications in environmental monitoring, according to the experts, as these have to be used in changing environmental conditions outside the laboratory. This circumstance must not lead to any deviation of the measurement results. Resistance to environmental influences is also very important for safety applications and agriculture. In the cosmetics industry, however, this criterion is not very important, since the measuring systems can be used in a sterile and defined environment and fewer environmental influences are expected to affect the measurement results. Ease of operation or operability plays an important role in all industries, since the measuring systems should be operable by ordinary employees who have no special training in the operation of these systems. For companies this is a decisive cost saving factor, if no major training of the employees for the operation of the measuring system is necessary.

The criteria related to the construction and production of the sensors are summarized in Figure 3c. The geometric dimensions of the sensor tend to play a more important role in safety applications, since mobile applications such as explosives' detection or people search are potentially more common there. This could also be the case for environmental monitoring, which is why the criterion for this field of application was also rated important. The weight of the sensors is also considered important for safety applications due to mobile applications. Rather unimportant ratings are, however, given this criterion for environmental and agricultural applications. Weight tends to play a smaller role for mobile applications than dimensions. Due to the large areas to be monitored by sensors, drone applications can play a central role for agricultural applications in the future, which is the reason for the relatively higher importance of this field. Weight would be a decisive factor here. The durability rates vary in their importance for all application fields between a narrow range of 2 for the cosmetics industry and 2.5 for environmental monitoring and food industry. Therefore, this criterion is important for all application fields. According to the experts, low cost production tends to play an important role in the food and cosmetics industries other than in the other fields of application rated as rather important. This could be due to the high competitive situation in this markets, where manufacturing costs play a major role in gaining a competitive advantage over the competition.

The statistical variances of the survey results are summarized in Figure 4. It can be seen that in some cases there is a high degree of uncertainty regarding the assessment of the importance of technical performance criteria in certain fields of application. The measurement time in the healthcare market and the cosmetics industry as well as the multi-sensing capability for the health care market, safety applications, agriculture and environmental monitoring should be emphasized, with variances higher than 2.

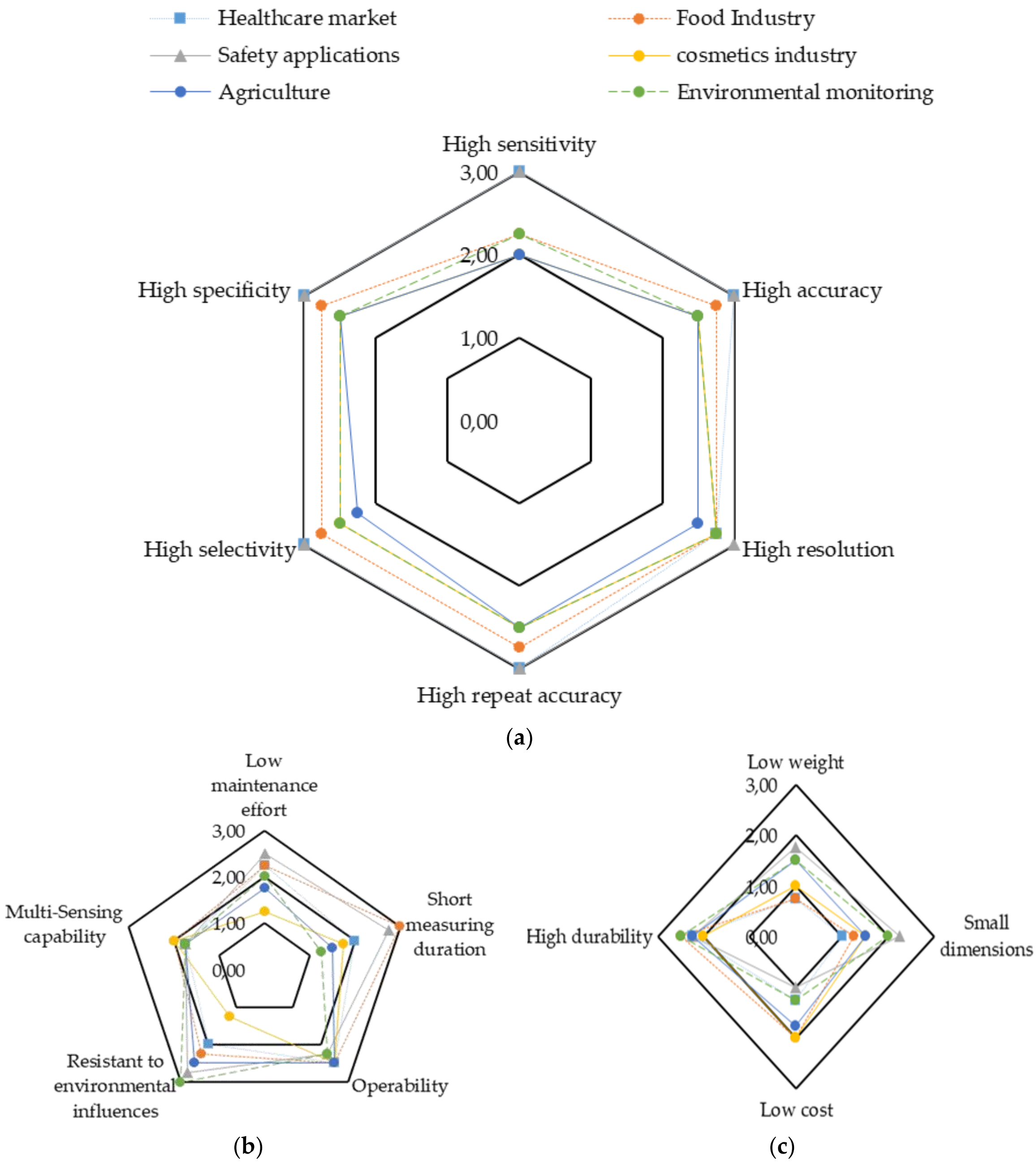

Figure 3. Evaluation of the requirement criteria on their importance (**a**) for the category of Measurement Quality; (**b**) for the category of handling; (**c**) for the category of technical construction and production; 0 = not important, 1 = rather unimportant 2 = important, 3 = very important; sample size: 11.

Variance	Healthcare market	Food Industry	Safety applications	cosmetics industry	Agriculture	Environmental monitoring
High sensitivity	0,00	0,92	0,00	0,67	0,67	0,92
High accuracy	0,00	0,25	0,00	0,33	0,33	0,33
High resolution	0,25	0,25	0,00	0,25	0,33	0,25
High repeat accuracy	0,00	0,25	0,00	1,00	1,00	1,00
High selectivity	0,00	0,25	0,00	0,33	0,92	0,33
High specificity	0,00	0,25	0,00	0,33	0,33	0,33
Low weight	0,92	0,92	1,58	0,67	1,00	1,67
Small dimensions	0,67	0,92	0,25	0,33	1,00	0,67
Low cost	0,25	0,67	0,67	0,00	0,25	0,92
High durability	0,92	0,33	0,92	0,00	0,92	0,33
Low maintenance effort	0,25	0,25	0,33	0,92	0,25	0,67
Short measuring duration	2,00	0,00	0,25	2,25	1,67	1,58
Operability	1,00	1,00	0,92	1,00	1,00	0,92
Resistant to environmental influences	0,67	0,92	0,25	0,92	0,33	0,00
Multi-Sensing capability	2,25	1,33	2,25	1,33	2,25	2,25

Figure 4. Statistical variances of the survey results shown in Figure 4 (red = higher values, green = lower values).

4. Conclusions

The results show that the requirements considered to be the most important are high specificity, high selectivity, high repeat accuracy, high resolution, high accuracy and high sensitivity. These criteria describing the measurement quality are classified as "important" or "very important" in every considered field of application. All these criteria except for the repeat accuracy are potentially better met by biosensors than by technical sensors. It can be concluded that biosensor technology has a high potential for application in the considered fields and will play a decisive role in the market for odor sensors. Specific fields of application that could be covered specifically with biosensors due to the high correspondence between requirement and performance profiles are healthcare and security applications. However, it must be taken into account that the development of biosensors should aim at an improved repeat accuracy. In addition to repeat accuracy, disadvantages of biosensors are seen in terms of durability, maintenance effort and resistance to environmental influences. These criteria are also rated as important or even very important for applications in those key markets and should be further developed. However, the manufacturing costs as the remaining criterion that is less well met by biosensors play a comparably less important role for healthcare and safety applications than in the other considered fields of application.

5. Summary and Outlook

In this paper, the specific market requirements for odor sensors were empirically assessed on the basis of 16 technical properties for various fields of application. The properties were classified into criteria concerning measurement quality, handling and operability as well as design and production related criteria. In comparison, the fulfillment of these criteria by biosensors were assessed in relation to the fulfilment of technical sensors. The aim of this comparison was to derive specific market potentials or fields of application with higher potential for biosensors. It turned out that the criteria for measurement quality are generally considered to be of high importance for all applications. In particular, biosensors have advantages in terms of sensitivity, selectivity, specificity, accuracy and resolution. Particularly these criteria are important for safety and healthcare applications. It can, therefore, be predicted that biosensors have comparatively high application potential in these markets. For example, it can open up new applications, such as the odor-based diagnosis of various diseases or the detection of traces of drugs or explosives in security-relevant facilities. However, disadvantages compared to technical sensors are seen in terms of durability, maintenance effort, repeat accuracy, cost and resistance to environmental influences. Durability is rated as important to very important for all fields of application considered. A special focus should, therefore, also be on the further development of biosensors to improve this criterion. For applications in the cosmetics, food and agricultural sectors, cost optimization are necessary, since these markets are very price-sensitive either due to the high number of throughput and measurement cycles or high competition. For outdoor applications, resistance to environmental influences must also be improved. They are seen, for example, in the application fields of environmental monitoring, safety, agriculture and also in the health sector. In contrast, analyses in the cosmetics sector are less sensitive to this criterion, since the interviewed experts believe that these analyses usually take place in defined environments where environmental influences can be minimized. With the results obtained, market specific application potential and development goals can be discussed more clearly on the basis of qualitative assessments shown in this paper. However, the authors would like to point out, that each application should be further regarded separately and can sometimes differ considerably from the requirement profiles of the respective application field. In addition, for investigations based on this results, weightings could be established for the criteria, the values of which could be determined from existing or future market volumes and the requirement profiles, for example. This paper can be referred to as a basis for further examinations.

Acckowledgement: The results shown in this paper were conducted within a research project supported by the Ministry of Economic Affairs, Labor and Housing of Baden-Wuerttemberg and Fraunhofer Gesellschaft. The authors gratefully acknowledge the financial support.

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