The State of Research on Electronic Nose and Electronic Tongue: A Global Analysis

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Abstract: Electronic nose and electronic tongue are two high-profile bionic instruments used in many fields, including the food and pharmaceutical industries. Here, we use bibliometrics to map a knowledge graph of electronic nose and electronic tongue research. The papers published from 1901 to 2017 were retrieved from the core database of the Web of Science. A total of 4713 papers from 92 countries on electronic nose research and 1008 papers from 62 countries on electronic tongue research were identified. Then, we show the research modes of the two research concepts at the national, institutional, and auctorial levels. Additionally, the evolution of electronic nose and electronic tongue research is presented, and the applications of these two research concepts to the food industry is reviewed. Finally, we present the research roadmap of electronic nose and electronic tongue. Both research topics will likely be vital for rapid food measurement

Keywords: Electronic nose; Electronic tongue; Bibliometrics; Knowledge graph; Food

1. Introduction

Sensor and computer technologies are currently at the forefront of science and technology. Electronic nose and electronic tongue are the perfect combination of sensors and computers.

An electronic nose is a device used to detect odors. In several industries, odor evaluation is usually conducted by human sensory analysis, chemosensors, or gas chromatography. Gas chromatography can detect volatile organic compounds, but the direct relationship between analytical results and the actual sense of smell has not been fully established. The research gap can be explained by the vast amounts of odorous components and their immeasurable potential interactions. Nonetheless, the identification procedure of an electronic nose is similar to human olfaction [1]. In particular, an electronic nose can perform recognition, discrimination, quantification, and similar applications. The electronic nose technology has undergone far-reaching developments and is currently used in many cases [2-4].

An electronic tongue is an instrument designed to measure and compare flavor. Chemical compounds responsible for gustation are detected by human taste receptors; comparatively, the sensors of an electronic nose can detect dissolved diverse compounds [5]. Similar to human receptors, the sensors of an electronic nose undergo a series of reactions. While the generated reactions differ from one another, the information acquired from each sensor is complementary. Finally, the results combined by the sensors generate a unique fingerprint. In biological mechanisms, gustatory signals are transducted by brain nerves in the form of electric signals. Electronic tongue sensors approach flavors similarly given that electric signals are generated with potentiometric variations. The perception and recognition of taste quality is based on the recognition or building of activated sensory nerve patterns in the brain and the gustation fingerprint of a product. This step is accomplished by the statistical software of the electronic tongue that can translate sensor data into taste patterns [6].

A knowledge graph is a series of graphs, often different from one another, that depicts the relationship between knowledge development and structure. The creation process requires visualization techniques, such as those provided by a bibliometric software, to generate the knowledge graph, describe the knowledge resource, and display the knowledge interconnections.

Bibliometrics is a comprehensive interdisciplinary science that aims to quantitatively analyze information by integrating mathematical, statistical [7], and philological methods. The main measurement objects of bibliometrics are document quantity, author number, and word count [8,9]. This analytical approach is suitable for evaluating the current research status of electronic nose and electronic tongue.

Electronic nose and electronic tongue are examples of bionic techniques. However, their development history and application to food remain unclear. In the present work, we construct knowledge graphs on the state of electronic nose and electronic tongue research covering the period until 2017 by using bibliometric analysis and current information on food applications. We review the advantages and disadvantages of electronic nose and electronic tongue, their application to food and big events, and their development as research topics on the basis of bibliometric analysis.

The aim of this study is to reveal the research status, consolidate the questions, and determine the future research direction of electronic nose and electronic tongue.

2. Materials and Methods

Raw data were retrieved from the core database of the Web of Science. Papers published from 1900 to 2017 were gathered by using the search terms “electronic nose” and “electronic tongue.” A total of 4713 papers on electronic nose published in 1987–2017 and 1008 papers on electronic tongue published in 1996–2017 were collected. Three types of software for bibliometric analysis and information visualization, namely, VOSviewer, HistCite, and CiteSpaceV, were applied.

3. Results and Discussion

3.1. Basic statistics

Figures 1(a) and 1(b) show the number of publications on electronic nose from 1987 to 2017 and electronic tongue from 1996 to 2017, respectively. Both figures also show the corresponding total global citation scores (TGCSs) per year for each research topic.

The number of publications on electronic nose increased yearly since 1987. The highest number of related papers (398) was published in 2016. Its TGCS continuously increased from 1987 to 2000, remained stable from 2001 to 2010, and decreased after 2010.

The number of publications on electronic tongue increased yearly since 1996 and then rapidly decreased between 2013 and 2014. Its TGCS increased from 1996 to 2006 and then decreased starting 2007. The highest number of related papers (150) was published in 2015 and 2016.

Figures 1(c) and 1(d) show the different types of publications of electronic nose and electronic tongue, respectively. The dominant document type was the article with 60% for electronic nose and 67.1% for electronic tongue. The other main document types were proceedings and reviews.

Figure 1. The basic situation of electronic nose and electronic tongue research. (a) Number and total global citation score of published papers on electronic nose during 1987-2017 per year; (b) Number and total global citation score of published papers on electronic tongue during 1996-2017 per year; (c) Types of published papers on electronic nose; (d) Types of published papers on electronic tongue.

3.2 National level

Figure 2(a) illustrates the publication outputs of the top 20 countries and their TGCSs for electronic nose research. From 1987 to 2017, China, USA, Italy, UK, Spain, and Germany were the top six publishing countries with 772, 667, 622, 364, 302, and 195 publications, respectively. The number of publications of the remaining 14 countries were close to one another. Among all countries, USA had the most number of TGCSs.

Figure 2(b) shows the publication outputs of the top 20 countries and their TGCSs for electronic tongue research. From 1996 to 2017, Spain, China, Russia, USA, and Brazil were the top five publishing countries with 192, 151, 109, 85, and 82 publications. Spain had the most TCGSs, although those of Russia, USA, Italy and Sweden were also numerous.

Figure 2(c) shows the number of global cooperation initiated for electronic nose research. USA, Italy, China, Spain, and UK cooperated the most times with many countries. By contrast, the other countries had not been extensively involved in global research cooperation. The comparison in Figure 2(d) shows that more cooperation among countries were initiated for electronic tongue research than that for electronic nose research. In this aspect, USA, Spain, Russia, China, and Italy cooperated with many countries.

The 26 countries with burst detections for electronic nose research from 2000 to 2017 are shown in Figure 2(e). China has the highest burst strength (44.5074) for the 2014–2017 period, followed by USA, England, and Sweden (26.7469, 22.8474, and 15.6699) but at different periods (2001–2004, 2000–2005, and 2000–2005, respectively). Only Iran, Netherlands, China, and Indonesia have burst detections for electronic nose research in 2017.

Figure 2(f) presents the 12 countries and their publication burst intensities for electronic tongue research from 1996 to 2017. Sweden has the highest burst strength (14.4687) in 1998–2005 followed by Russia (13.806) in 1996–2002. None of the countries have burst detections in 2017.

USA dominated the status of electronic nose research, as evidenced by its second largest number of published papers and the highest overall TGCS among all countries. Furthermore, USA holds an important status in electronic tongue research, considering that it ranked fourth in terms of number of publications and second in terms of TGCS. Spain, Russia, Italy, and Sweden also highly influenced the status of electronic tongue research. With regard to global collaboration, USA, China, and Italy have established relationships with numerous countries to accomplish electronic nose and electronic tongue research. With regard to burst strength, Iran, Netherlands, China, and Indonesia have shown high potentials in electronic nose research.

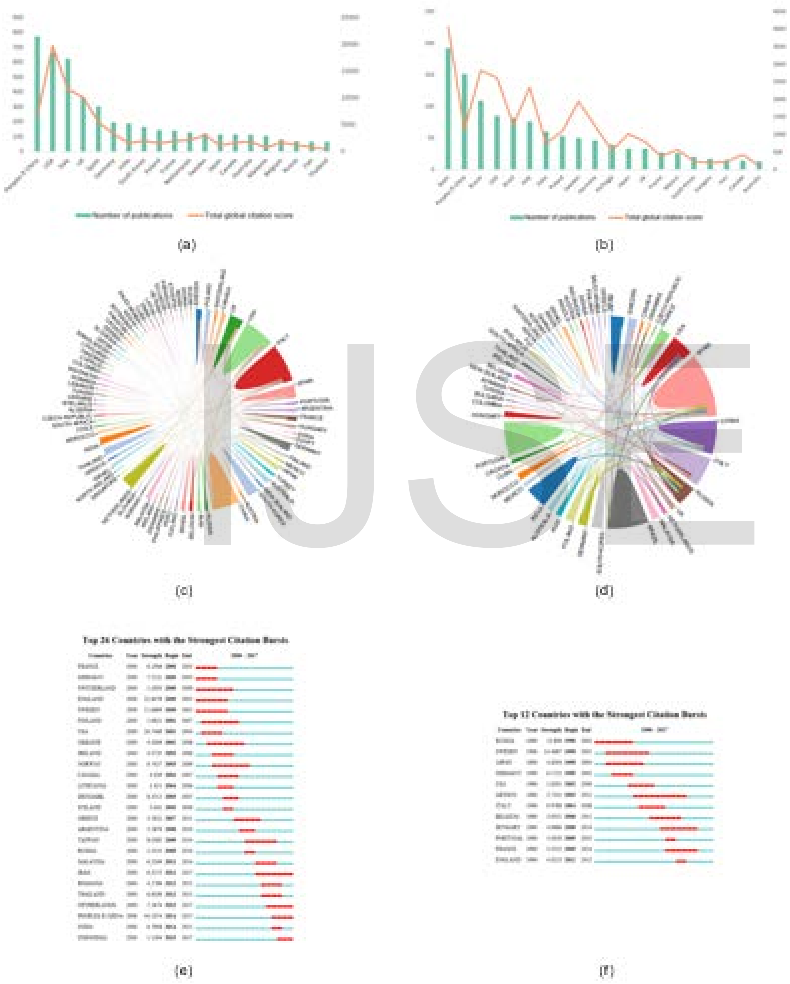

Figure 2. The situation of electronic nose and electronic tongue research at the national level. (a) Top 20 highest publishing countries and total global citation score of electronic nose; (b) Top 20 highest publishing countries and total global citation score of electronic tongue; (c) Global cooperation of the electronic nose research; (d) Global cooperation of the electronic tongue research; (e) Twenty-six countries with the strongest citation bursts from 2000 to 2017 in electronic nose research ; (f) Twelve countries with the strongest citation bursts from 1996 to 2017 in electronic tongue research.

3.3 Institutional level

Figure 3(a) presents the top 20 publishing institutions engaged in electronic nose research. Zhejiang University ranked first with 132 publications, followed by University of Rome Tor Vergata with 119 publications. The number of publications of the other institutions in the list were less than 100. California Institute of Technology had the most number of TGCSs, but with 51 publications only. University of Rome Tor Vergata, University of Warwick, Zhejiang University, and Cranfield University also had high numbers of TGCS.

Figure 3(b) shows the top 20 publishing institutions engaged in electronic tongue research. Saint Petersburg State University ranked first with 77 publications, followed by Universitat Autònoma de Barcelona with 51 publications. The number of publications from the other countries in the list were less than 45. Notably, Saint Petersburg State University also ranked first in terms of TGCSs, followed by Linköping University and University of Rome Tor Vergata.

Figures 3(c) and 3(d) show the number of cooperation established among institutions for electronic nose and electronic tongue research, respectively. Several modes of inter-institutional cooperation were initiated for electronic nose research, such as those by Zhejiang University, University of Rome Tor Vergata, Brescia University, Cranfield University, Caltech, University of Amsterdam, Chongqing University, University of Milan, and several other reputable centers. With regard to electronic tongue research, only two groups of institutional cooperation have been reported. Universidade do Minho, University of Valladolid, Saint Petersburg State University, Universitat Autònoma de Barcelona, and Linköping University were some of the institutions that participated in electronic tongue research cooperation.

Figure 3(e) shows the 23 institutions with the strongest citation bursts for the 2010–2017 period, in which the burst strengths seem to have similar intensities. Only Tianjin University, Northwest A&F University, and Southwest University generated citation bursts in 2017. As shown in Figure 3(f), Saint Petersburg State University, Linköping University, and Universitat Autònoma de Barcelona attained the top three highest strengths (15.0833, 11.2583, and 7.3711) but at different periods (1996–2004, 1998–2005, and 2005–2008, respectively). Citation bursts were detected for Jadavpur University, Ctr Dev Adv Comp, Universidade Estadual De Campinas, and ITMO University in 2017.

On the basis of the number of publications and TGCSs of institutions, Zhejiang University, University of Rome Tor Vergata, University of Warwick, Cranfield University, and Caltech highly influenced the status of electronic nose research. In particular, Caltech focused on the elements of electronic nose technology and its application. The cooperation model of electronic nose research is big-scale and international in scope. Tianjin University, Northwest A&F University, and Southwest University have also shown potentials in electronic nose research.

With regard to electronic tongue research, Saint Petersburg State University, Linköping University, and University of Rome Tor Vergata play important roles. The publications from Saint Petersburg State University focused on the application of electronic tongue technology, while those from Linköping University and University of Rome Tor Vergata emphasized the application of electronic tongue from the higher-level perspective of technology upgrade. The cooperation model of electronic tongue is similar to that of electronic nose. Jadavpur University, Ctr Dev Adv Comp, Universidade Estadual De Campinas, and ITMO University have shown potentials in electronic tongue research.

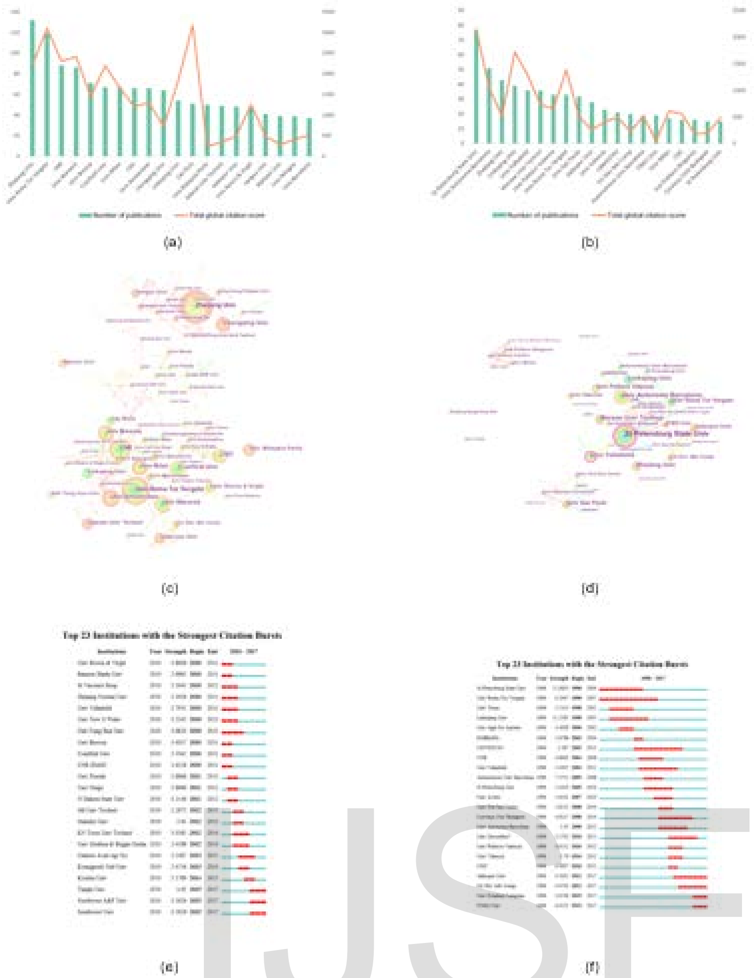

Figure 3. The situation of electronic nose and electronic tongue research at institutional level. (a) Top 20 highest publishing institutions and total global citation score in electronic nose research; (b) Top 20 highest publishing institutions and total global citation score in electronic tongue research; (c) The cooperation among institutions in electronic nose research; (d) The cooperation among institutions in electronic tongue research; (e) Top twenty-three institutions with the strongest citation bursts in electronic nose research from 2010 to 2017; (f) Top twenty-three institutions with the strongest citation bursts in electronic tongue research from 1996 to 2017.

3.4 Auctorial level

Figure 4(a) shows the top 20 authors with the highest number of publications and their TGCSs for electronic nose research. Di Natale C ranked first with 107 publications, followed by D'Amico A (82 publications), Paolesse R (72 publications), and Wang J (71 publications). Di Natale C, Gardner JW, and D'Amico A were the top three authors with the most number of TGCSs. Notably, in Figure 4(b) on electronic tongue research, del Valle M ranks first with 72 publications, but Legin A has the most number of TGCSs despite the lower number of publications at 69. The publications of the other authors were less than 45. Rudnitskaya A, del Valle M, Winquist F, and Vlasov Y also had high numbers of TGCS.

Figure 4(c) shows the cooperation among authors for electronic nose research. Several clusters of auctorial relationship were established. The largest cluster involved Di Natale C, Paolesse R, D'Amico A, Macagnano A, Sterk PJ, Pardo M, Sberveglieri G, Magan N, Gardner JW, Tudu B, Bandyopadhyay R, Bhattacharyya N, and other authors. The two other big clusters are for the following: The first group is composed of Zhao JW, Chen QS, Li J, Hui GH, and other authors. The second group involved Tian FC, Zhang L, Wang P, Wang J, and other authors. The other clusters were small in scale and involved few authors. Figure 4(d) shows the cooperation among authors for electronic tongue research. Legin A and del Valle M both led the research initiatives of biggest cluster. The second largest cluster involved Rodriguez-Mendez ML, de Saja JA, Apetrel C, and other authors. The other clusters for electronic tongue research were small in scale similar to those for electronic nose research.

Figure 4(e) shows the top 38 authors with the strongest citation bursts for electronic nose research from 2010 to 2017. Namiesnik J has the highest strength (5.9957) during the 2015–2017 period. The burst strengths of the other authors were all under 5.0. Hassan M, Jia PF, Zhang D, Wisniewska P, Yuan YH, Sliwinska M, Namiesink J, Yue TL, Wardencki W, and Dymerski T were the only authors with bursts detected in 2017. Figure 4(f) shows the top 46 authors with the strongest citation bursts for electronic tongue research from 1996 to 2017. Vlasov YG, Krantz-Rulcker C and Vlasov Y were the authors with top three highest burst strengths (9.812, 9.7218, and 9.1376) but at different periods (1996–2001, 2001–2005, and 1996–2005). Ceto X, Bhattacharyya N, Tudu B, Bandyopadhyay R, and Wesoly M were the only authors with bursts detected in 2017.

On the basis of the overall number of publications and TGCS, Gardner JW highly influenced the status of electronic nose research until 2017. His published work included articles on the application of electronic nose and a number of reviews. Di Natale C, D'Amico A, and Paolesse R also greatly contributed to electronic nose research. In addition, Zhang D, Namiesink J, and Yue TL have shown great potential in electronic nose research. With regard to electronic tongue research, del Valle M, Legin A, Rudnitskaya A, and Winquist F are regarded important figures considering the number of their publications and TGCSs. Ceto X, Bhattacharyya N, Tudu B, Bandyopadhyay R, and Wesoly M have also shown potential in electronic tongue research.

The auctorial cooperation model of electronic nose and electronic tongue research are similar to those at the institutional level.

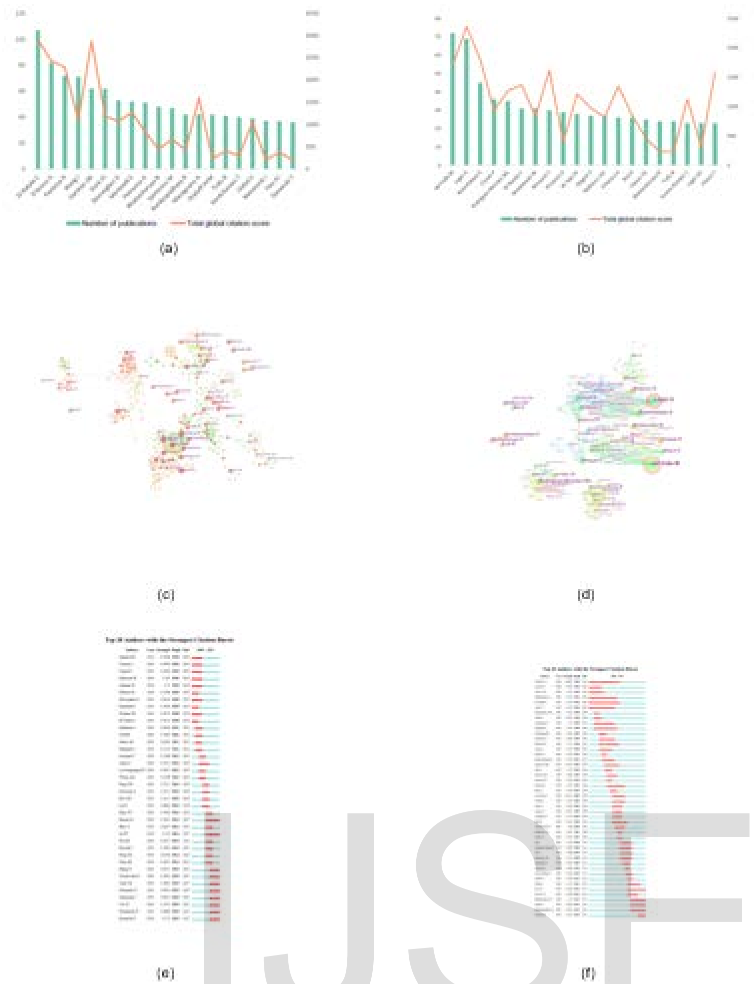

Figure 4. The situation of electronic nose and electronic tongue research at auctorial level.(a) Top 20 highest publishing authors and total global citation score in electronic nose research; (b) Top 20 highest publishing authors and total global citation score in electronic tongue research; (c) The cooperation among authors in electronic nose research; (d) The cooperation among authors in electronic tongue research; (e) Top thirty-eight authors with the strongest citation bursts in electronic nose research from 2010 to 2017; (f) Top forty-six authors with the strongest citation bursts in electronic tongue research from 1996 to 2017.

3.5 Performance of keywords

The keywords “discrimination,” “classification,” “quality,” “volatile compounds,” and “gas sensors” have high densities in electronic nose research (Figure 5(a)), whereas “discrimination,” “classification,” “taste sensor,” “system,” “water,” “wine,” “electronic nose quality,” and “identification” dominated the electronic tongue research (Figure 5(b).

Figure 5(c) shows the top 23 keywords with the strongest citation bursts for electronic nose research from 2010 to 2017. “Film” has the highest burst strength (12.4447) during the 2010–2012 period, followed by “breath test,” “gas sensor array,” “gc m,” and “asthma” (8.4686, 8.3313,7.7696, and 7.1721) but at different periods (2013–2014, 2012–2013, 2015–2017, and 2011-2013, respectively). “Voc” and “gc m” were the two keywords with burst detections in 2017.

Figure 5(d) shows the top 50 keywords with the strongest citation bursts for electronic tongue research from 1996 to 2017. “Pattern recognition” (8.9161) “chemical sensor” (8.3569), “food”

(7.6974), "discrimination" (7.5781), and "electronic tongue" (7.4968) have the highest burst strengths for the periods 2000–2004, 1999–2009, 2015–2017, 2014–2017, and 1996–2002, respectively. "Identification," "quality," "discrimination," "near infrared spectroscopy," "phenolic compound," "taste," "chemometrics," "prediction," "data fusion," "geographical origin," "food," "sensor evaluation," and "bioelectronic tongue" have burst detections in 2017.

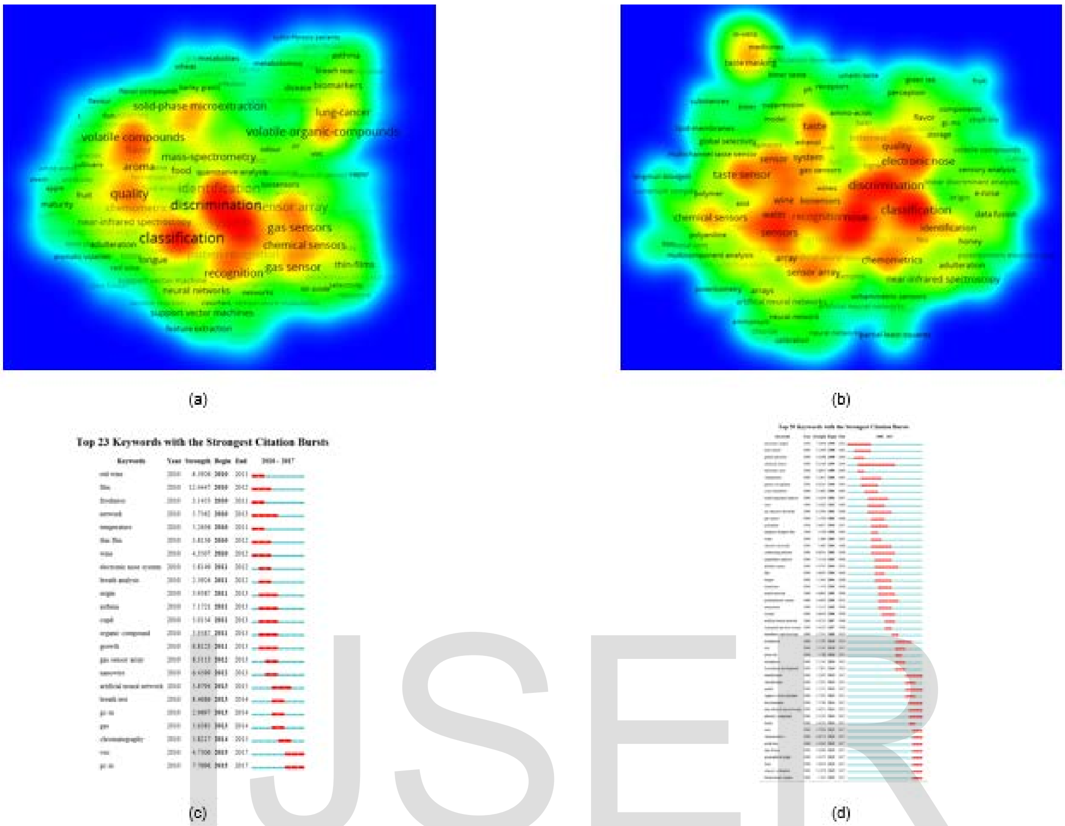

Figure 5. Major keywords of electronic nose and electronic tongue research and burst detection results. (a) Density of major keywords in electronic nose research; (b) Density of major keywords in electronic tongue research; (c) Twenty-three keywords with burst detection in electronic nose research during 2010-2017; (d) Fifty keywords with burst detection in electronic tongue research during 1996-2017.

3.6 Performance of socuments and journals

Document co-citation analysis involves a similarity-measurement of documents and utilizes citation analysis to assess semantic similarities across documents at different levels (e.g., global and individual) [10,11]. This approach identifies, follows the development, and forecasts the foreground of popular research fields [12-15]. On the basis of the patterns derived from the document co-citation network analysis of electronic nose research (Figure 6(a)), the cited references were divided into 14 main clusters. Clusters #0 to #13 were labeled as follows: "review article," "breath analysis," "computational method," "array size," "signal processing technique," "electronic nose," "data analysis," "bp network," "headspace mass spectroscopy," "transfer component analysis," "early detection," "mammalian olfactory system," "oxide-based electronic nose," and "botanical origin." Then, the cited references of electronic tongue research (Figure 6(b)) were divided into 13 main clusters. Cluster #0 to #12 were labeled as follows: "quality evaluation," "potentiometric sensor arrays-a review," "artificial taste sensor," "bitter solution," "geographical origin," "discrete ion-selective sensor," "pharmaceutical application," "analytical application," "multicomponent solution," "microelectrode array," "amperometric biosensor," and "disposable optical tongue".

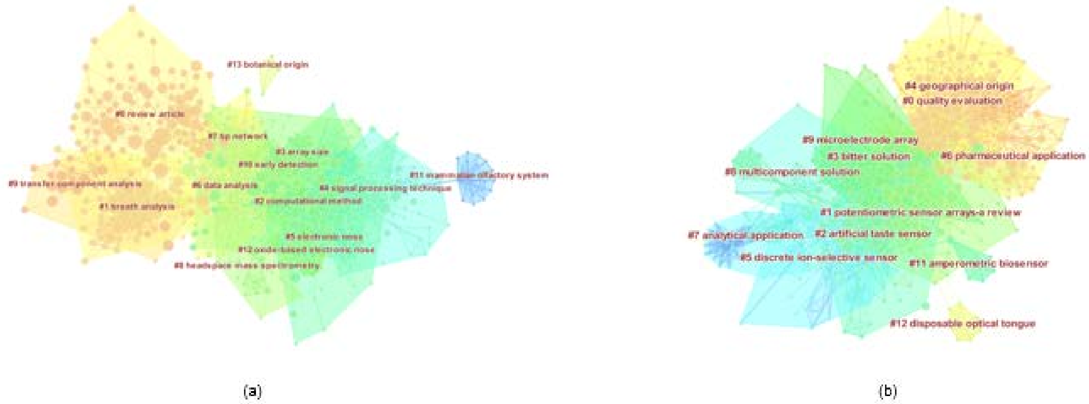

Figure 6. Document co-citation network analysis of electronic nose (a) and electronic tongue (b) research.

Table 1 presents the 10 journals that published the highest number of papers on electronic nose. Sensors and Actuators B-Chemical published 578 papers as of 2017 and ranked first among 1555 journals, followed by Sensors (172 publications), IEEE Sensors (89 publications), and Food Chemistry (85 publications). The other journals have less than 80 publications. The 10 journals can be divided as follows: 4 from USA, 2 from Switzerland, 2 from England, and 2 from Netherlands. Table 2 lists the top 10 most frequently cited references on electronic nose research, all of which were written before 2010. The top three cited references were as follows: A Brief History of Electronic Noses (367 citations), Electronic Nose: Current Status and Future Trends (340 citations), and Analysis of Discrimination Mechanisms in the Mammalian Olfactory System Using a Model Nose (335 citations). The other references were cited less than 200 times.

Table 1. Top 10 highest publishing journals of electronic nose research

Rank	Journal	Number	Percentage	IF(2016)	Country
1	Sensors and Actuators B-Chemical	578	12.210	5.401	Switzerland
2	Sensors	172	3.633	2.677	Switzerland
3	IEEE Sensors Journal	89	1.880	2.512	USA
4	Food Chemistry	85	1.796	4.529	England
5	Analytica Chimica Acta	73	1.542	4.950	Netherlands
6	Journal of Agricultural and Food Chemistry	57	1.204	3.154	USA
7	Journal of Food Science	48	1.014	1.815	USA
8	Journal of Food Engineering	44	0.929	3.099	England
9	Analytical Chemistry	42	0.887	6.320	USA
10	Biosensors & Bioelectronics	39	0.824	7.780	Netherlands

Table 2. Top 10 most cited references of electronic nose research.

Rank	Title	Number	Year	Journal
1	A Brief-history of Electronic Noses	367	1994	Sensors and Actuators B-Chemical
2	Electronic Nose: Current Status and Future Trends	340	2008	Chemical Reviews
3	Analysis of Discrimination Mechanisms in the Mammalian Olfactory System Using a Model Nose	335	1982	Nature
4	Applications and Advances in Electronic-Nose Technologies	191	2009	Sensors
5	A 21st Century Technique for Food Control: Electronic Noses	184	2009	Analytica ChiImica Acta
6	'Electronic Noses' and Their Application to Food	181	1998	Food Science and Technology-Lebensmittel-Wissenschaft & Technologie
7	Lung Cancer Identification by the Analysis of Breath by means of an Array of Non-selective Gas Sensors	173	2003	Biosens Bioelectron
8	The Electronic Nose Applied to Dairy Products: a	160	2003	Sensors and

	Review			Actuators B-Chemical
9	Cross-Reactive Chemical Sensor Arrays	147	2000	Chemical Reviews
10	An Electronic Nose in the Discrimination of Patients with Asthma and Controls	142	2007	Journal of Allergy and Clinical Immunology

Table 3 presents the 10 journals that published the highest number of papers on electronic tongue. Sensors and Actuators B-Chemical published 124 papers as of 2017 and ranked first among 356 journals, followed by Talanta (50 publications), Analytica Chimica Acta (41 publications), and Sensors (34 publications). The 10 journals can be divided as follows: 3 from Netherlands, 3 from England, 2 from Switzerland, 1 from USA, and 1 from Austria. Table 4 lists the top 10 most frequently cited references on electronic nose research. The top three cited references were as follows: An Electronic Tongue Based on Voltammetry (162 citations), Discrimination of Tea by Means of a Voltammetric Electronic Tongue and Different Applied Waveforms (105 citations), and Nonspecific Sensor Arrays ("Electronic Tongue") for Chemical Analysis of Liquids (IUPAC Technical Report) (105 citations). The other references were cited less than 100 times.

Table 3. Top 10 highest publishing journals of electronic tongue research

Rank	Journal	Number	Percentage
1	Sensors and Actuators B-Chemical	124	12.217
2	Talanta	50	4.926
3	Analytica Chimica Acta	41	4.039
4	Sensors	34	3.350
5	Electroanalysis	31	3.054
6	Biosensors & Bioelectronics	25	2.463
7	Food Chemistry	24	2.365
8	International Journal of Pharmaceutics	19	1.872
9	Journal of Food Engineering	18	1.773
10	Microchimica Acta	15	1.478

Table 4. Top 10 most cited references of electronic tongue research.

Rank	Title	Number	Year	Journal
1	An electronic tongue based on voltammetry	162	1997	Analytica Chimica Acta
2	Discrimination of tea by means of a voltammetric electronic tongue and different applied waveforms	105	2001	Sensors and Actuators B-Chemical
3	Nonspecific sensor arrays ("electronic tongue") for chemical analysis of liquids (IUPAC Technical Report)	105	2005	Pure and Applied Chemistry
4	Sensor arrays for liquid sensing - electronic tongue	99	2007	Analyst

	systems			
5	A hybrid electronic tongue	99	2000	Analytica ChiImica Acta
6	Tasting of beverages using an electronic tongue	97	1997	Sensors and Actuators B-Chemical
7	Electronic tongues for environmental monitoring based on sensor arrays and pattern recognition: a review	91	2001	Analytica Chimica Acta
8	Taste sensor	83	2000	Sensors and Actuators B-Chemical
9	Evaluation of Italian wine by the electronic tongue: recognition, quantitative analysis and correlation with human sensory perception	81	2003	Analytica Chimica Acta
10	Electronic tongues and their analytical application	71	2002	Analytical and Bioanalytical Chemistry

The first paper on electronic nose entitled Development of an Electronic Nose was written by Shurmer H, Fard A, Barker J, Bartlett P, Dodd G, and Hayat U and published in 1987 by Physics in Technology. This paper in the document format of a review presented the principle, sensors, and design of electronic nose [16]. Meanwhile, the first paper on electronic tongue entitled A Biosensor Array Based on Polyaniline was published in 1996. This paper presented a type of biosensor array that can be used to fabricate an electronic tongue [17].

The main research topics of the top 10 highly published journals for electronic nose and electronic tongue research include "sensors," "food," and "analytical chemistry." A Brief History of Electronic Noses, the most cited reference by electronic nose research papers, presented a review of the research efforts for electronic nose from 1961 to 1993. The paper provided a definition of electronic nose (i.e., "an instrument which comprises an array of electronic chemical sensors with partial specificity and an appropriate pattern-recognition system, capable of recognizing simple or complex odors") and summarized the applications of electronic nose technology [18]. Of the top 10 cited references, 7 are in the form of reviews and 3 in the form of research articles. Meanwhile, the most cited reference on electronic tongue is the Electronic Tongue Based on Voltammetry, in which "a prototype of an electronic tongue based on the combination of voltammetry was designed [19]." Research articles dominated the top 10 most cited references on electronic tongue.

3.7 Application to the food industry

On the basis of TGCS, electronic nose research can be divided into three stages: stage I (1987–2000), stage II (2001–2010), and stage III (2011–2017). Similarly, electronic tongue research can be divided into two stages: stage I (1996–2006) and stage II (2007–2017). Figure 7 depicts the substantial differences across the different stages. For instance, as the years progressed, the focus of electronic nose and electronic tongue research shifted from pattern recognition and equipment elements to application. The shifts are consistent with the development trends for new kinds of technology. The most common pattern recognition techniques for electronic nose and electronic tongue are principal component analysis (the dominant topic), cluster analysis, and artificial neural networks.

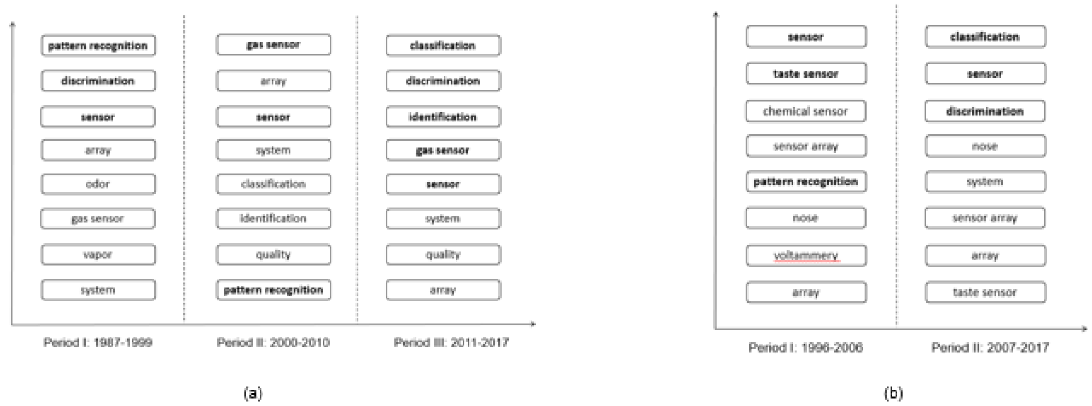

Figure 7. Top key words at different stages in electronic nose research (a) and electronic tongue research (b).

Electronic nose has short response time and fast detection speed, and the results of detection by electronic nose can be repeated. Furthermore, it has high detection specificity. For example, electronic nose can better detect toxic gases compared with human abilities. Lim SH et al. developed an optoelectronic nose that can differentiate 19 toxic industrial chemicals within 2 minutes [20]. The advantages of electronic tongue are similar to those of electronic nose, as both simulate human sensory organs. However, the low-maturity levels of electronic nose and electronic tongue technology limit their application. Considering that olfactory and gustatory mechanisms are not fully understood, the corresponding technologies are still underdeveloped. High cost also limits the application of both technologies. Nonetheless, electronic nose and electronic tongue have been used in many ways. For example, electronic nose can be applied to the aerospace, agricultural, fire control, environmental, food, and pharmaceutical industries. Meanwhile, electronic tongue can be applied in the food, pharmaceutical, tobacco, pesticide, and medical (pathogenic microorganism) industries. However, on the basis of a number of published reports, electronic nose and electronic tongue are mostly applied to the food industry.

Figure S2 shows that electronic nose and electronic tongue are mainly applied for the classification, discrimination, and identification of food. Tables 5 and 6 show some sample applications. An example is the analysis of food items, such as beverage, meat, fruit, oil, grain, and dairy products. Taurino AM et al. used electronic nose with microbiological methods to correlate and analyze different types of dry salami, and they found good discrimination across three different clusters [21]. Santos JP et al. successfully identified pig feeding and ripening time of Iberian ham by using electronic nose [22]. O'Connell M et al. developed a portable electronic nose to determine the freshness of Argentinean hake [23]. Oshita S et al. examined odors that emanated from the La France pear by using an electronic nose and found strong relationship with headspace gas chromatograph [24]. Olsson J et al. detected ochratoxin A and deoxynivalenol in barley grains with an electronic nose [25].

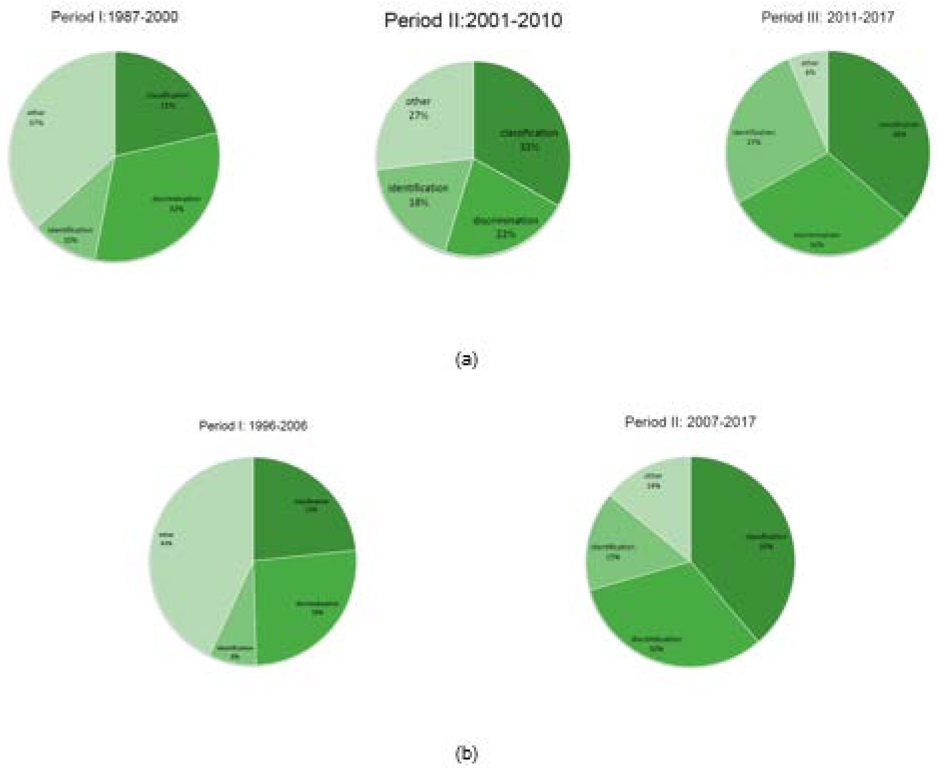

Figure 8. Main application for food at different stages with electronic nose (a) and electronic tongue (b).

Table 5. Examples about application of electronic nose for food industry.

Application case		Aim of use	Pattern recognition	Reference
Beverage	Tea	Quality standardization	PCA, FCM	26
	Black tea	Quality evaluation	RBF network	27
		Fermentation monitoring	PCA, SVD,2NM, MDM	28
	Japanese green tea	Identification of coumarin-enriched and particular flavor	PCA, CA	29
	Wine	Discrimination of vintage years	PCA	30
		Spoilage monitor	PCA, PLS, SLDA	31
Meat product	Salami	Cluster discrimination	PCA	21
	Iberian hams	Identification of pig feeding and ripening time	PCA, ANN	22
	Fish	Freshness determination	PCA	23
Fruit	'La France' pears	Discrimination of odors		24
Grain	Barley	Detection and quantification of ochratoxin A and deoxynivalenol	PCA,PLS	25

Table 6. Examples about application of electronic tongue for food industry.

Application case		Aim of use	Pattern	Reference
Beverage	Chinese tea	Classification according to geographical origin and grade level	PCA	32
	Black tea	Classification of different grades of black tea	PCA, ANN	33
	wine	Quality assessment of ethanol, vodka and eau-de-vie	PCA,PLS	34
Dairy products	Goat milk	Identification of adulteration	PCA, LDA, ANN	35
Meat product	Sparus Auratus	Freshness analysis	PCA, ANN, PLS	36
Oil product	Olive oils	Evaluation of different storage conditions	PCA, LDA	37
		Bitterness analysis	PCA, PLS-DA	38
	Edible oils	Discrimination of different edible oils	PCA, KNN	39

Beverages are the other main detection object in food analysis of electronic nose and electronic tongue. For instance, Dutta R et al. analyzed five kinds of tea with different qualities by using an electronic nose [26]. Tudu B et al. applied electronic nose techniques based on the radial basis function neural network to evaluate the quality of black tea [27]. Bhattacharyya N et al. monitored 81 fermentation cycles of black tea with an electronic nose [28]. Ziyin Y et al. identified the flavor of different types of Japanese green tea by using an electronic nose [29]. Natale C et al. used an electronic nose to discriminate the vintage years of different wines and recognized the red wine types sourced from different vineyards [30]. Cynkar W et al. used head-space mass spectrometric electronic nose to monitor red wine spoilage [31]. He W applied potentiometric all-solid-state electronic tongue to identify teas from different geographical origins and the quality grades of these teas [32]. Palit M et al. classified different grades of black tea with a voltammetric electronic tongue [33]. Legin A et al. applied the multi-sensor electronic tongue system was to classify and recognize vodka and ethanol [34]. Dias LA et al. used an electronic tongue to evaluate whether goat milk is adulterated with bovine milk [35]. Gil L et al. found that electronic tongue is a potential tool for fish freshness determination [36]. Cosio MS et al. developed a recognition tool built by electronic nose and electronic tongue to evaluate olive oil stored in different conditions and at different periods [37]. Apetrei C combined electronic nose, electronic tongue, and electronic eye for the bitterness analysis of different types of olive oil at varying degrees [38]. Oliveri P et al. proposed a voltammetric electronic tongue for the discrimination of different edible oils [39].

Figure 9 presents the research roadmap of electronic nose and electronic tongue, especially in the food industry. Most of the developmental timing of electronic nose is earlier than that of electronic tongue. The first paper on the electronic nose was published in 1987, then the first paper on food discrimination by using an electronic nose was published in 1992. Subsequently, the feasibility of using an electronic nose to discriminate different types of coffee was demonstrated, and the success rate was higher than 80% [40]. The most cited paper on electronic nose was published in 1994. The first paper on food classification by using electronic nose was published in 1996. Borjesson T et al. used electronic nose to classify 235 samples of different kinds of grain. The results were compared with the opinion of grain inspectors, and the matching ratio was higher than 75% [41].

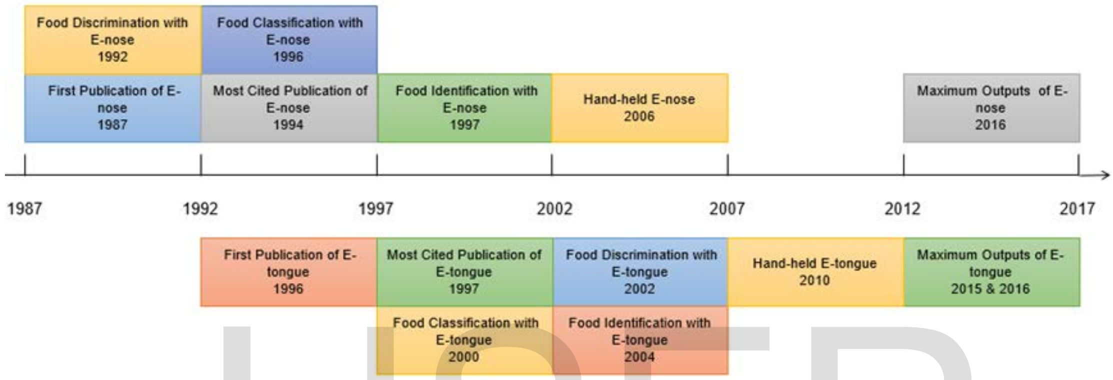

Figure 9. Roadmap of electronic nose and electronic tongue research.

The first paper on the electronic tongue was published in 1996. Notably, the most cited publication on the electronic tongue was published a year later in 1997. That same year, for the electronic nose, the first paper on food identification entitled Advanced Analytical Tools in Seafood Science (from the book, Seafood from Producer to Consumer, An Integrated Approach to Quality) was also published. The first paper on food classification by using an electronic tongue was published in 2000. Subsequently, the combined system of using the electronic nose and electronic tongue was applied to the classification of two kinds of milk [42]. The first paper on food discrimination by using an electronic tongue was published in 2002, including different brands of red wine [43]. The first paper on food and electronic tongue, which focused on the identification of soft drinks, was published in 2004 [44]. Hand-held of electronic nose and electronic tongue were also reported in 2006 and 2010, respectively. The number of publications on electronic nose and electronic tongue both increased until 2016

4. Conclusions

We first constructed knowledge graphs of electronic nose and electronic tongue research with bibliometric methods. The visualized information on the derived basic statistics, levels (nations, institutions, and authors), document types, and journal publications are discussed. We also presented adequate information on the application of electronic nose and electronic tongue to the food industry.

Research outputs of electronic nose has increased dramatically since 1987 whereas that of electronic tongue has started in 1996. USA, Italy, China, Spain, Russia, and Sweden are the six most active countries engaged in electronic nose and electronic tongue research. Much collaboration has been reported among institutions and authors. Most publications on electronic nose focused on topics such as discrimination, classification, quality, volatile compounds, and gas sensors, whereas those on electronic tongue include discrimination, classification, taste sensor, system, water, wine, electronic nose quality, and identification. A series of burst detection of keywords is conducted, and findings show that the application of electronic nose and electronic tongue is currently a popular research topic. The knowledge graphs also provide visual information on the global scientific trends of electronic nose and electronic tongue research in many aspects.

We presented in detail the advantages and disadvantages and applications of electronic nose and electronic tongue. Examples of their application to the food industry are presented. The roadmap of electronic nose and electronic tongue application to the food industry is also generated. The research roadmap suggest that electronic nose and electronic tongue can conveniently and effectively detect various kinds of food. Electronic nose and electronic tongue will become important instruments in the food industry, particularly as tools for rapid measurement and screening. The combination of electronic nose and electronic tongue research can provide more information on their simultaneous applicability. However, massive data preprocessing and chemometric analyses are required to overcome limitations in baseline shifts, instrument drifts, variable collinear inconsistencies, and different signal scales. Thus, further improvements and experimentations are needed to upgrade both technologies.

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