UNIVERSITA DEGLI STUDI DI TERAMO UNITE

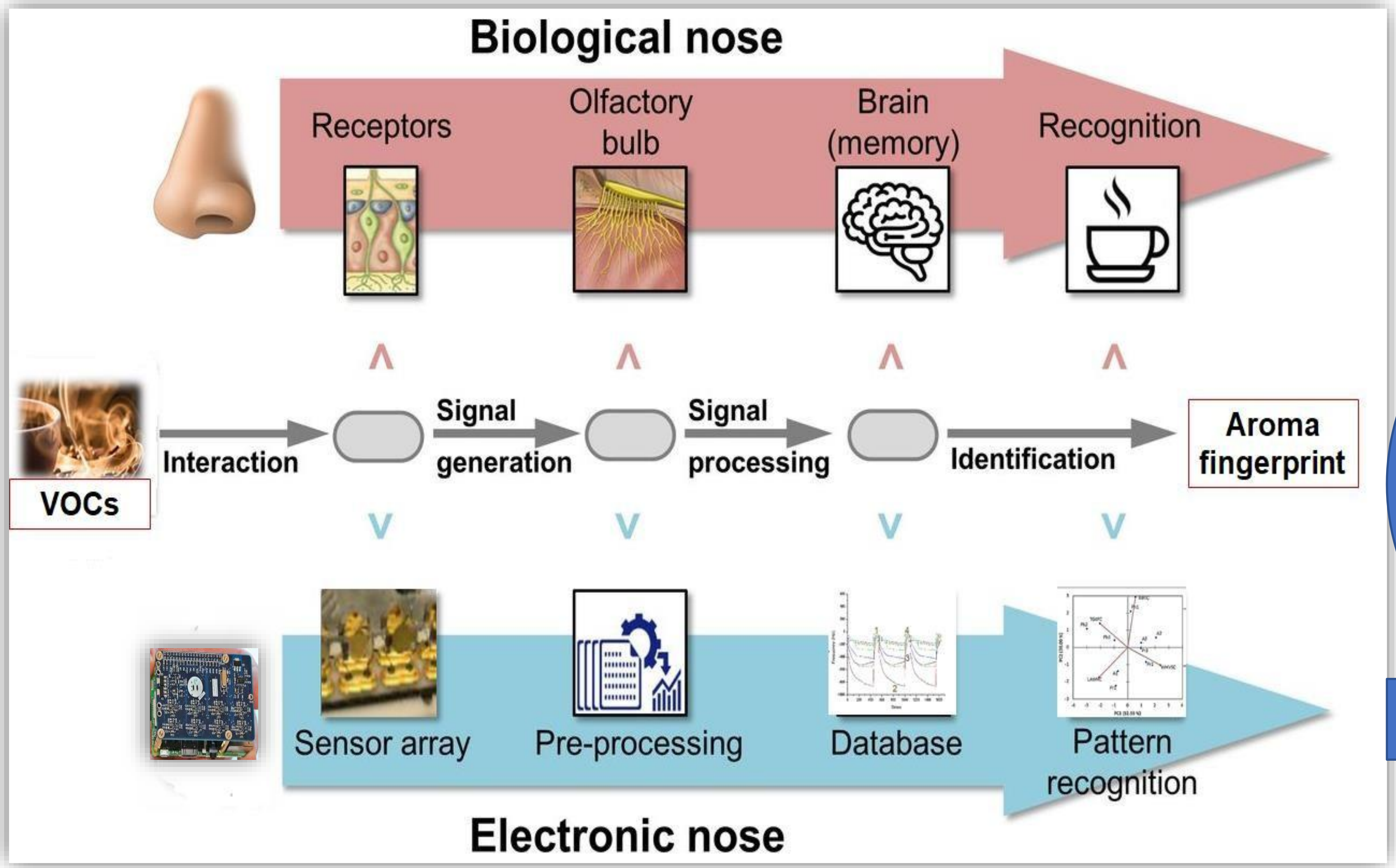
Electronic nose (E-nose)

- Electronic noses are engenireed to mimic the mammalyan olfactory sistem
- Instrumentent designed to allow detection and classification of aroma mixtures
- Refers to the capability of reproducyng human senses using sensor arrays and pattern recognition system

✓ *cosmetic industry control*

✓ *environmental monitoring for air quality control*

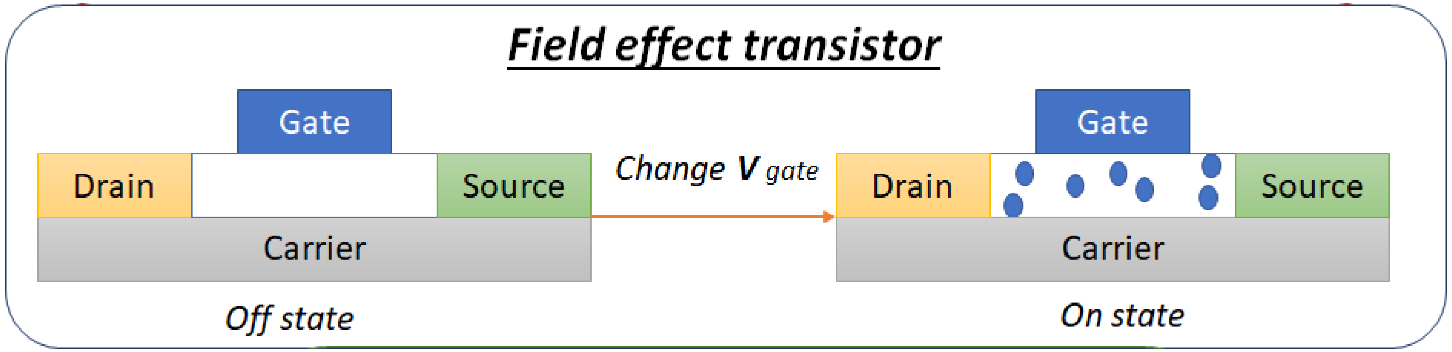
✓ *food quality and safety control*

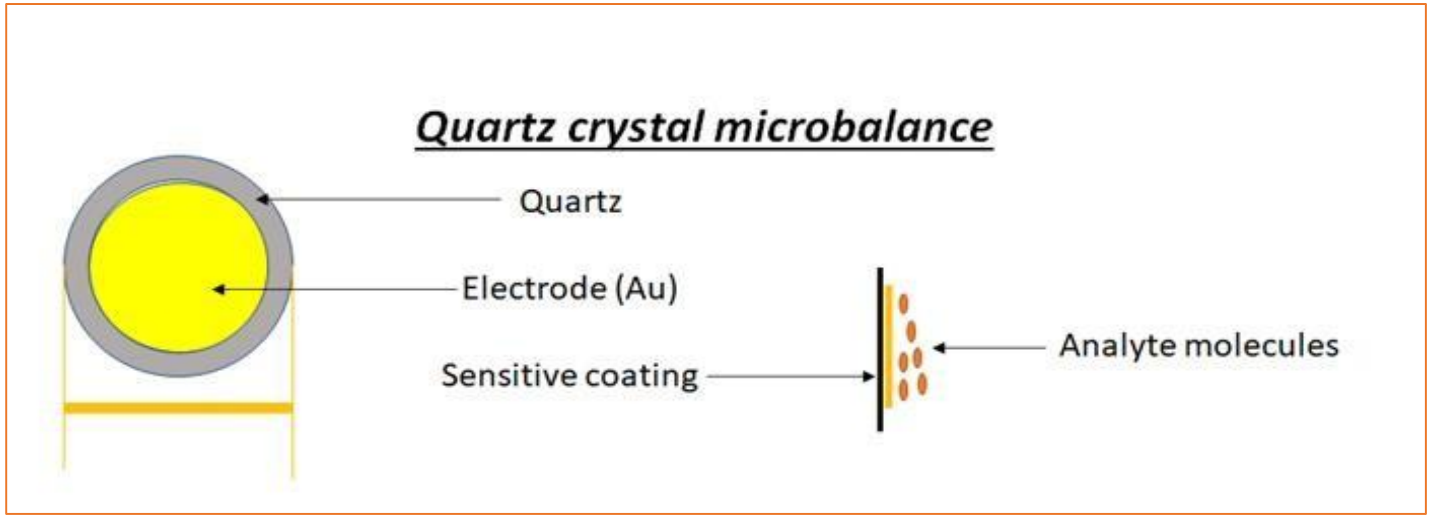


'An electronic nose is an instrument, which comprises an array of electronic chemical sensors with partial specificity and an appropriate pattern-recognition system, capable of recognizing simple or complex odors' [1]

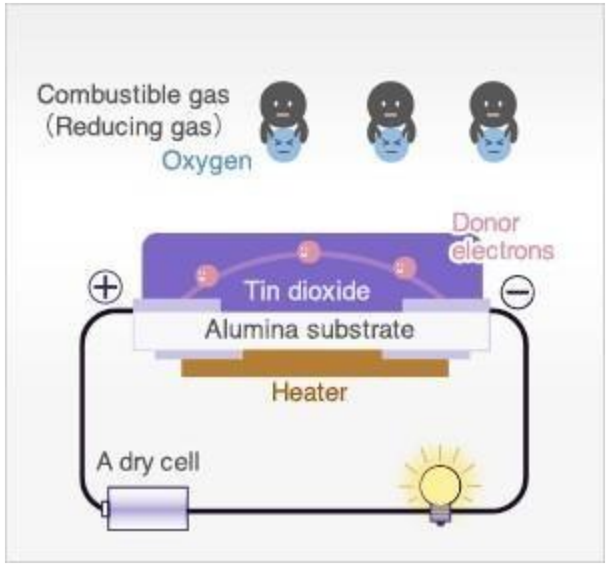
[1] Gardner, Julian W., and Philip N. Bartlett. "A brief history of electronic noses." *Sensors and Actuators B: Chemical* 18.1-3 (1994): 210-211.

....Different type of transducer for gas sensing....



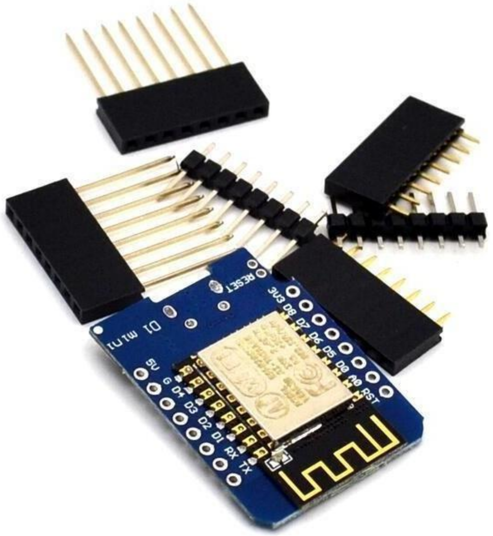


- ✓ *low costs*
- ✓ *easy realization*
- ✓ *ability to work in real-time*
- ✓ *short analysis times*



MOS SENSORS

Metal oxide semiconductors



Constituted by three main parts:

- Ceramic substrate
- Heating wire or thermistor
- Semiconducting metal oxides film (Zn, Co, etc.)

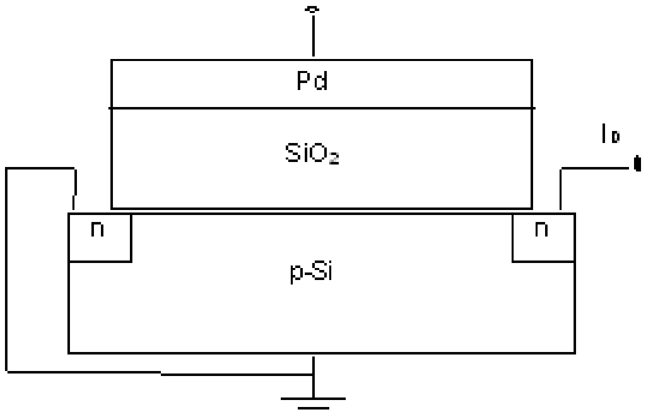
They measure conductivity changes onto the surface of the sensors induced by gases. Sensitive to combustion gases (hydrocarbons, NO, CO). Work at 300-400°C. An exchange between the gas and the oxygen on the film causes a change in resistance dependent on the adsorbed gas.

MOSFET SENSORS

Field effect metal oxides transistors

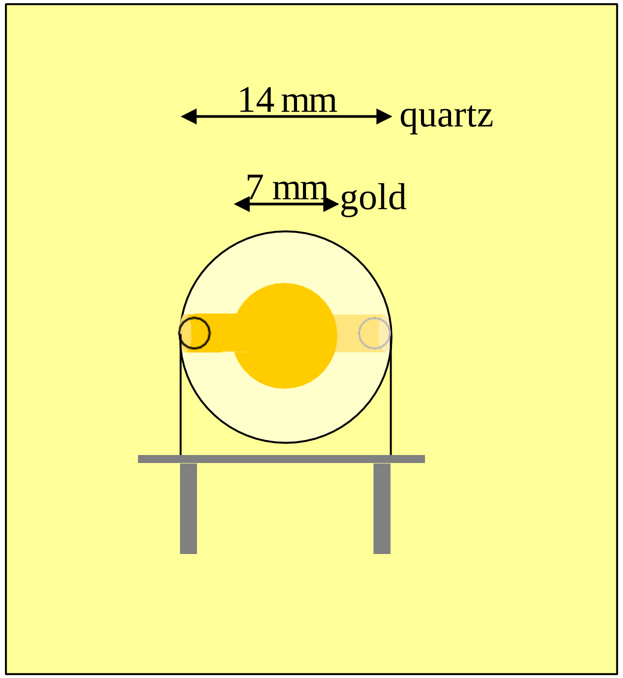
Made by 3 parts:

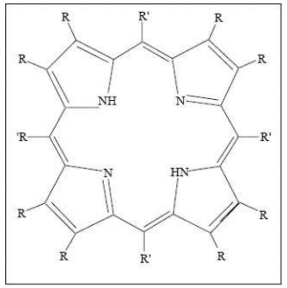
- Semiconducting Silicon
- Insulating silica layer
- Catalytic metal (Pt, Pd, etc.)



Work as a transistor at applied potential at 140-170°C. Sensitive to compounds containing hydrogen (amines, aldehydes, esters, chetons, aromatics ed alcohols). Whwn a polar molecules interacts with the metal the electric field is modified and a change in current occurs. The device output is the voltage necessary to have the current back at the initial value.

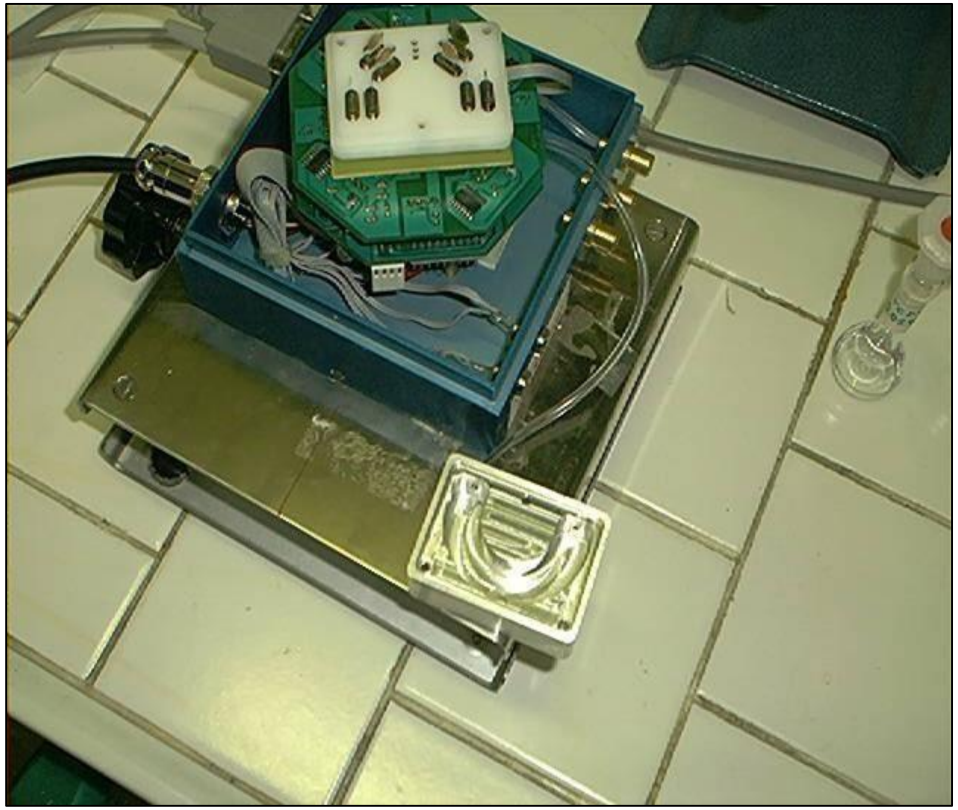
Piezoelectric System Electronic nose





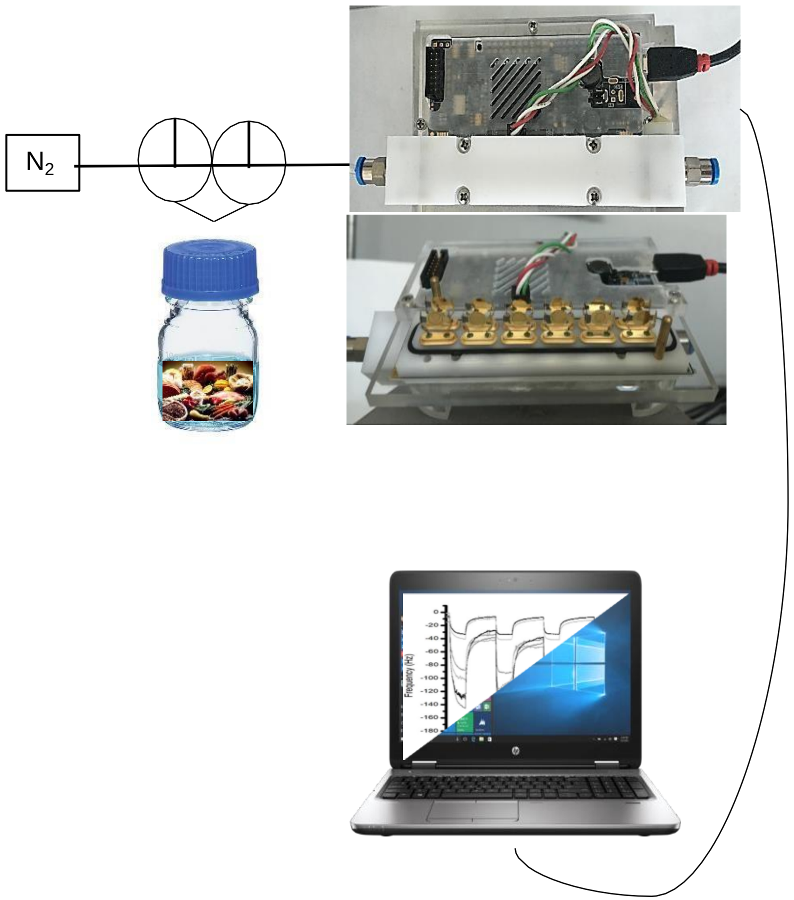
Butiloxy Tetra Phenyl Porphyrin

Cu
Co
Zn
Mn
Fe
Sn
Ru
Cr



UNITE

Measurement system

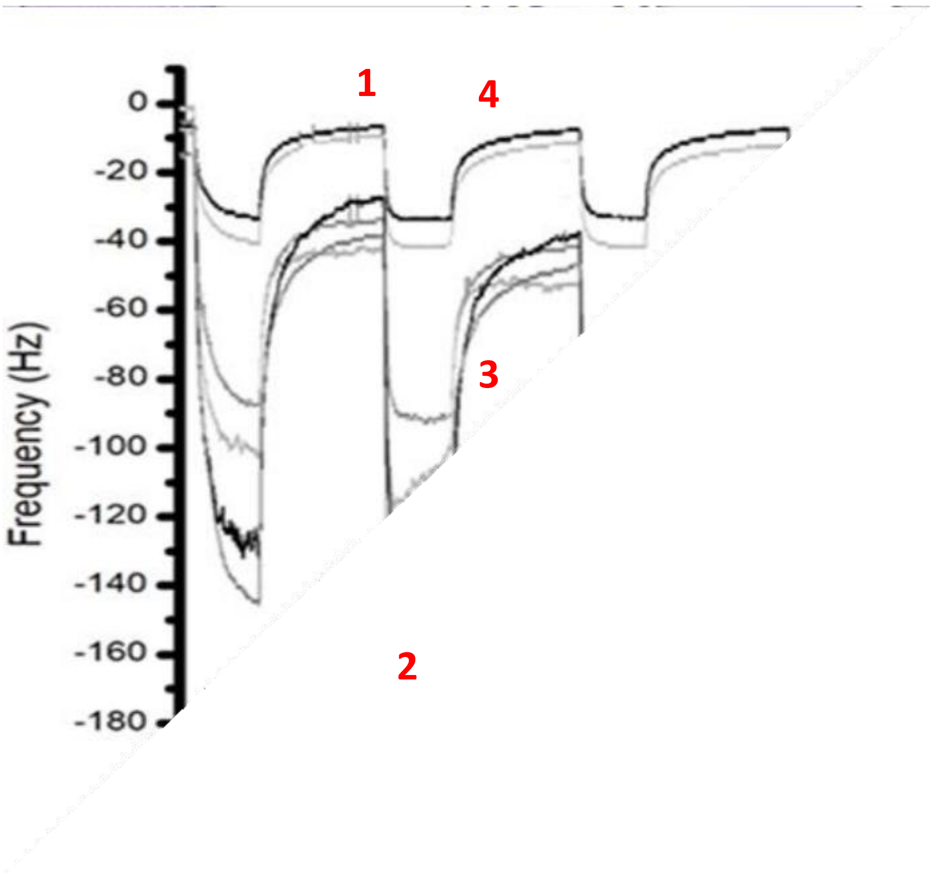


1.Start

2.Decrease

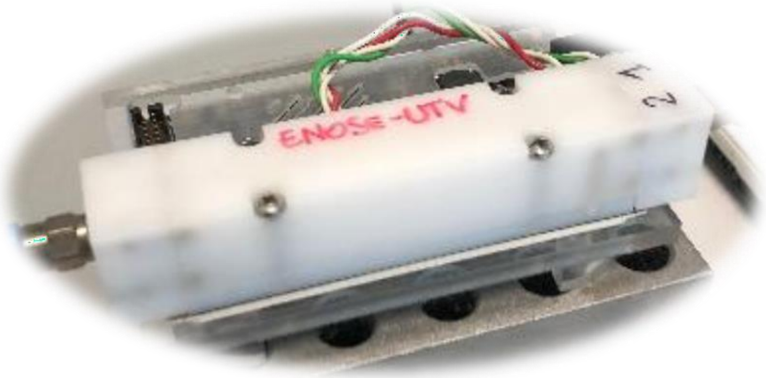
3.Equilibration

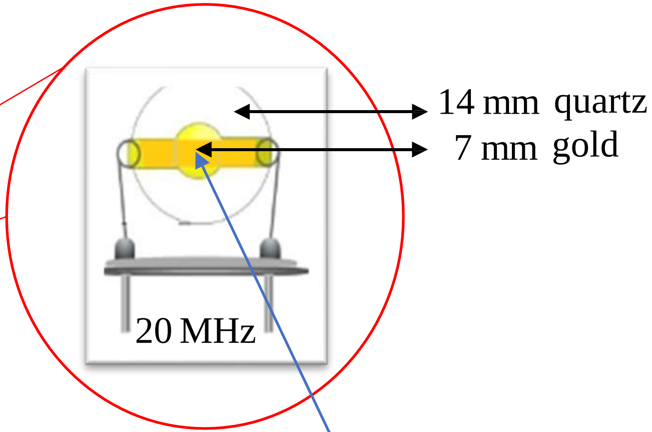
4.Baseline

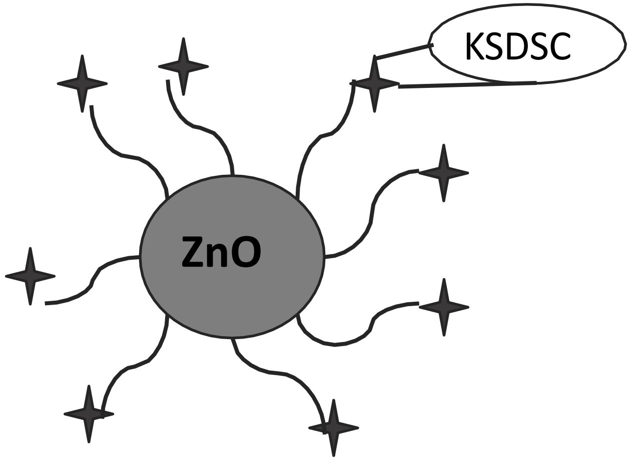


Frequency signals recorded with ZnONPs-peptides testing food

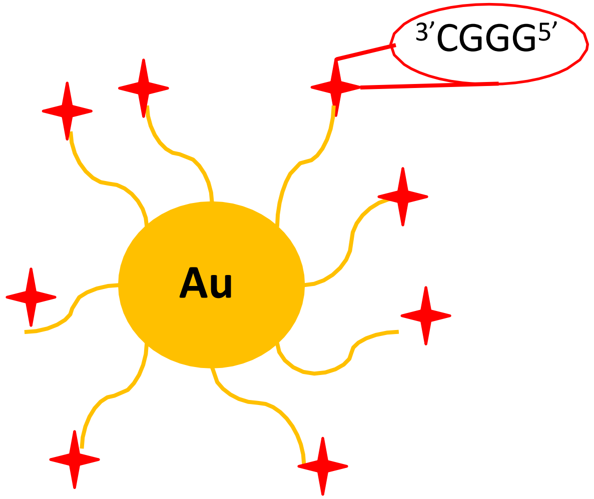
Electronic nose



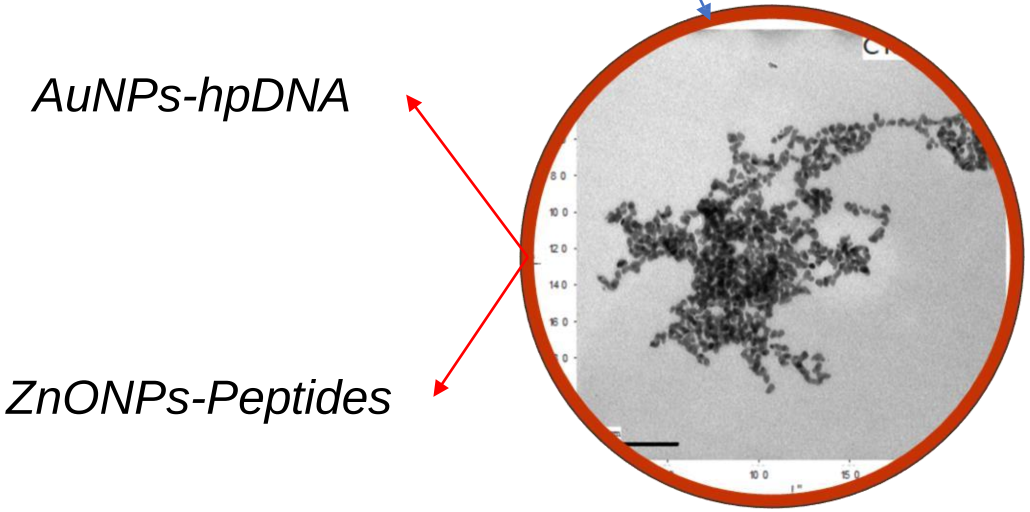




ZnONPs-Peptides



AuNPs-hpDNA



UNITE

Electronic nose sensor arrays

GNP-Peptide based

- **AuNP-Glutathione**
- **AuNP-Cys-Gly**
- **AuNP-Cys**
- **AuNP-Thioglicolic Acid**
- **AuNP-Cys-Arg-Gln-Val-Phe**
- **AuNP-Cys-Ile-His-Asn-Pro**
- **AuNP-Cys-Ile-Gln-Pro-Val**
- **AuNP**

Porphyrin based

- **Cu-Buti-TPP**
- **Co-Buti-TPP**
- **Zn-Buti-TPP**
- **Mn-Buti-TPP**
- **Fe-Buti-TPP**
- **Sn-Buti-TPP**
- **H_2-Buti-TPP**
- **Mg-Buti-TPP**

UNITE

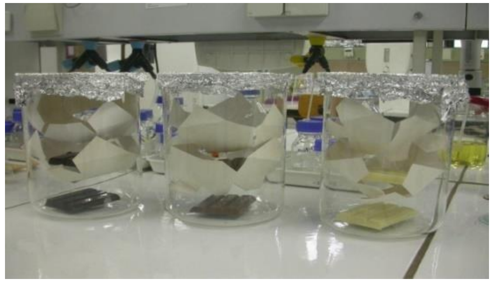
- Temperature: 40°C
- Equilibration time: 10 min
- 15g in 100 mL lab bottle grated and melted
- N_2 = 4 L/h

Standard Samples
VS
Off-flavoured samples

PLS-DA analysis

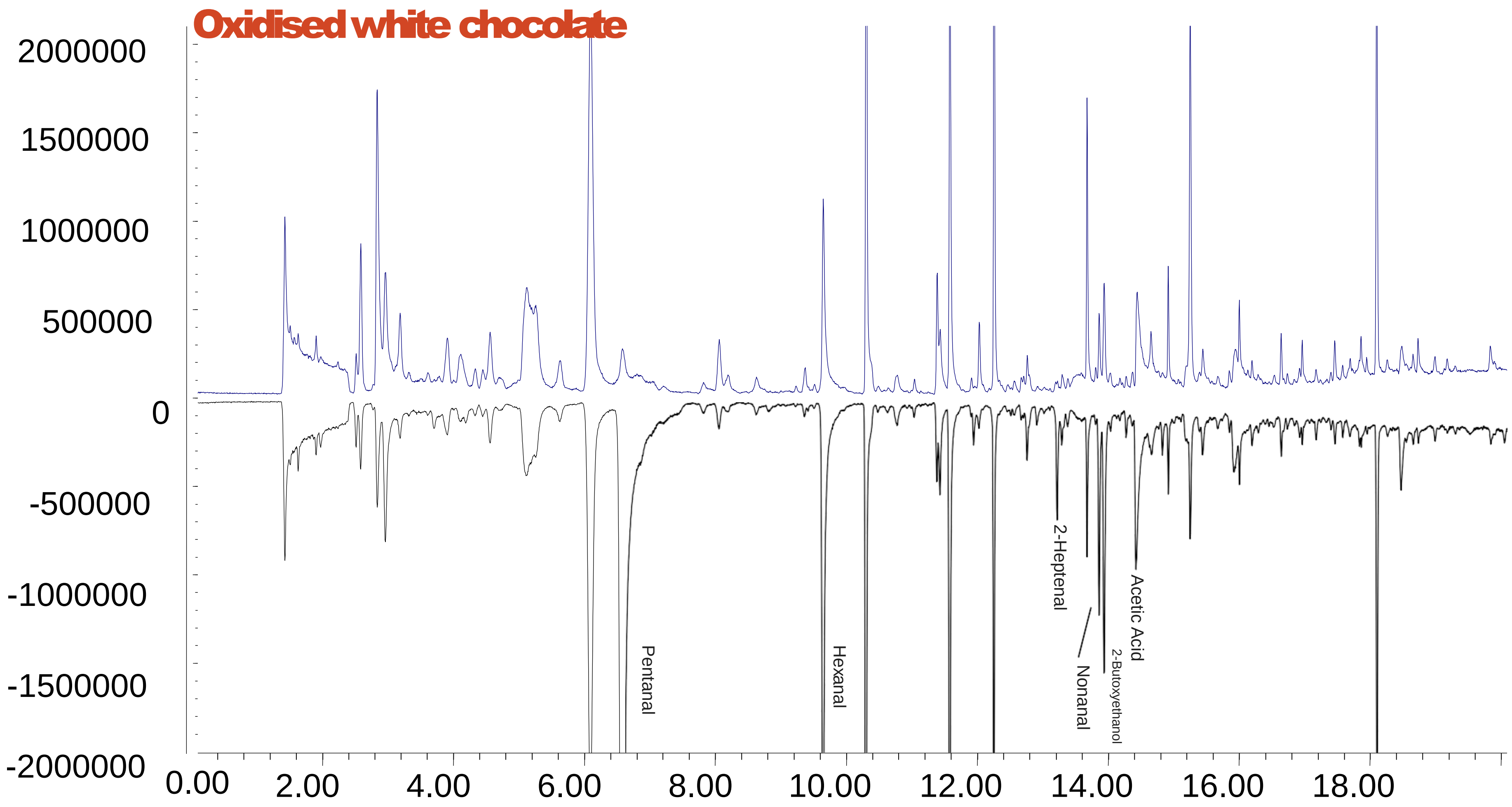
UNITE

Off-Flavour	Process
3-methylbutanal	**Fermentation volatiles**
Phenylacetaldehyde	
Acetic Acid	**Conching process**
Tetramethylpyrazine	**Roasting Process**
2-acetylpyrrole	
2-nonenal	**Fat related (oxidation)**
2,4-decadienal (t,t)	

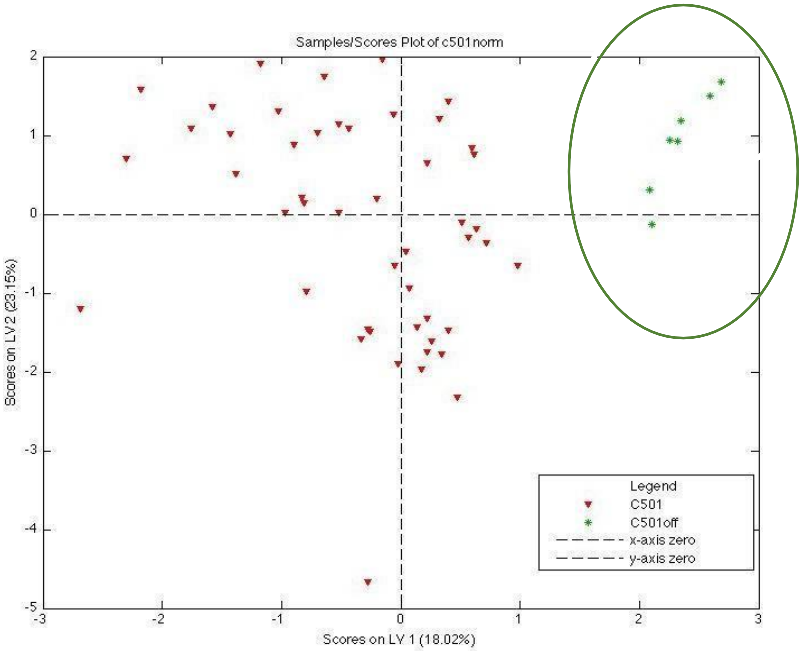


Off-flavours were preliminarily added in the cocoa butter to achieve the concentration of 125 ppm. One tea spoon of contaminated cocoa butter was then added to 400 g of chocolate to obtain an estimated final concentration in the sample of ~ 6ppm.

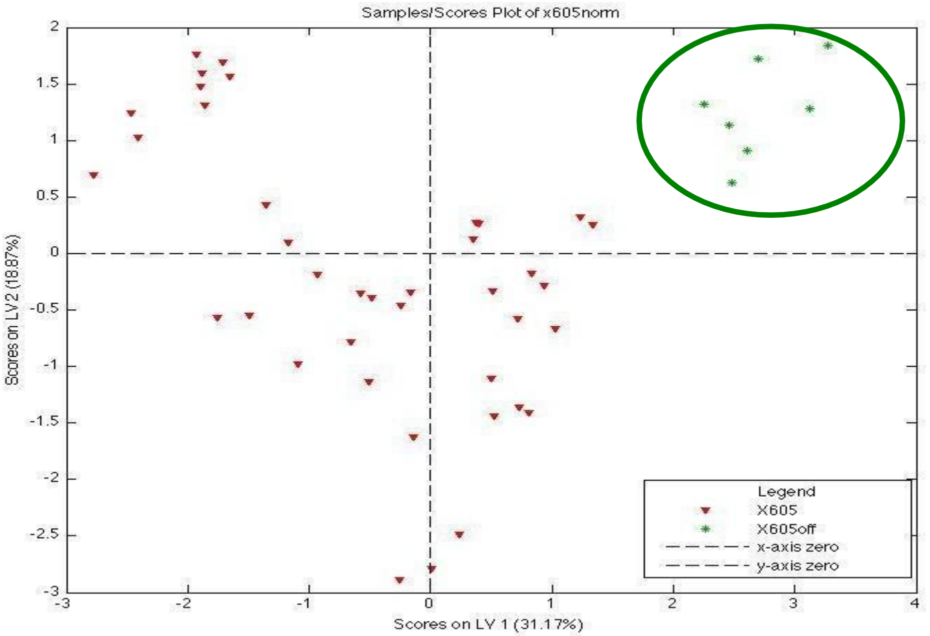
Real samples

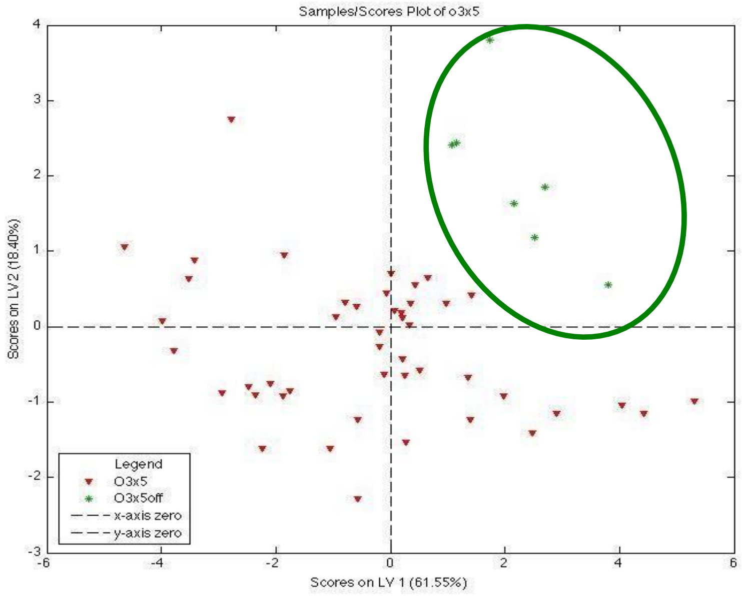


Dark Chocolate



White Chocolate





Milk Chocolate

AuNP-Peptide vs. Porphyrin PLS-DA analysis

GNP-Peptide based

	Regular	Off Flavours	% Correct
Regular	48	0	100
Off flavours	0	7	100

Tot. Correct:

	Regular	Off Flavours	% Correct
Regular	39	0	100
Off flavours	0	7	100

Tot. Correct:

	Regular	Off Flavours	% Correct
Regular	51	1	98
Off flavours	0	7	100

Tot. Correct:

Porphyrin based

	Regular	Off Flavours	% Correct
Regular	14	1	93
Off flavours	1	9	90

Tot. Correct:

	Regular	Off Flavours	% Correct
Regular	13	1	92
Off flavours	4	8	67

Tot. Correct:

	Regular	Off Flavours	% Correct
Regular	15	1	94
Off flavours	4	8	67

Tot. Correct:

D. Compagnone, M. Faieta, D. Pizzoni, C. Di Natale, et al *Sensors and Actuators B*, 207, 1114, 2015.

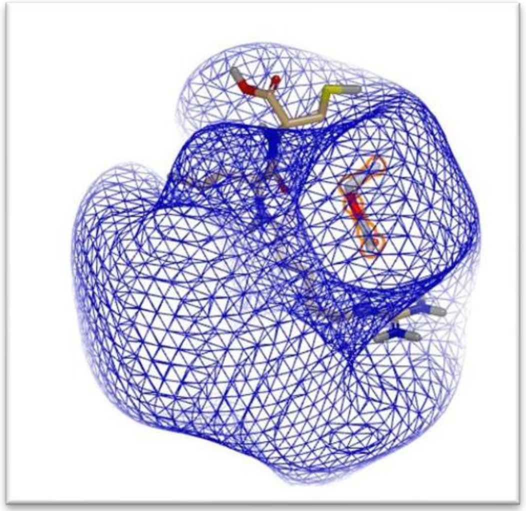
UNITE

Virtual screening Peptides

6 Peptides studied
(KSDSC, WHVSC, LGFDC, IHRIC, LAWHC, TGKFC)

VS

14 volatile compounds
(different chemical classes, shapes, dimensions, hydrophobicity)



- Docking box generation 10 conformers for each peptide for identification of most probable bond sites and energy quantification involved in the docking simulation
- From 1 to 200 conformers for each volatile compound
- Binding score: average of all conformers

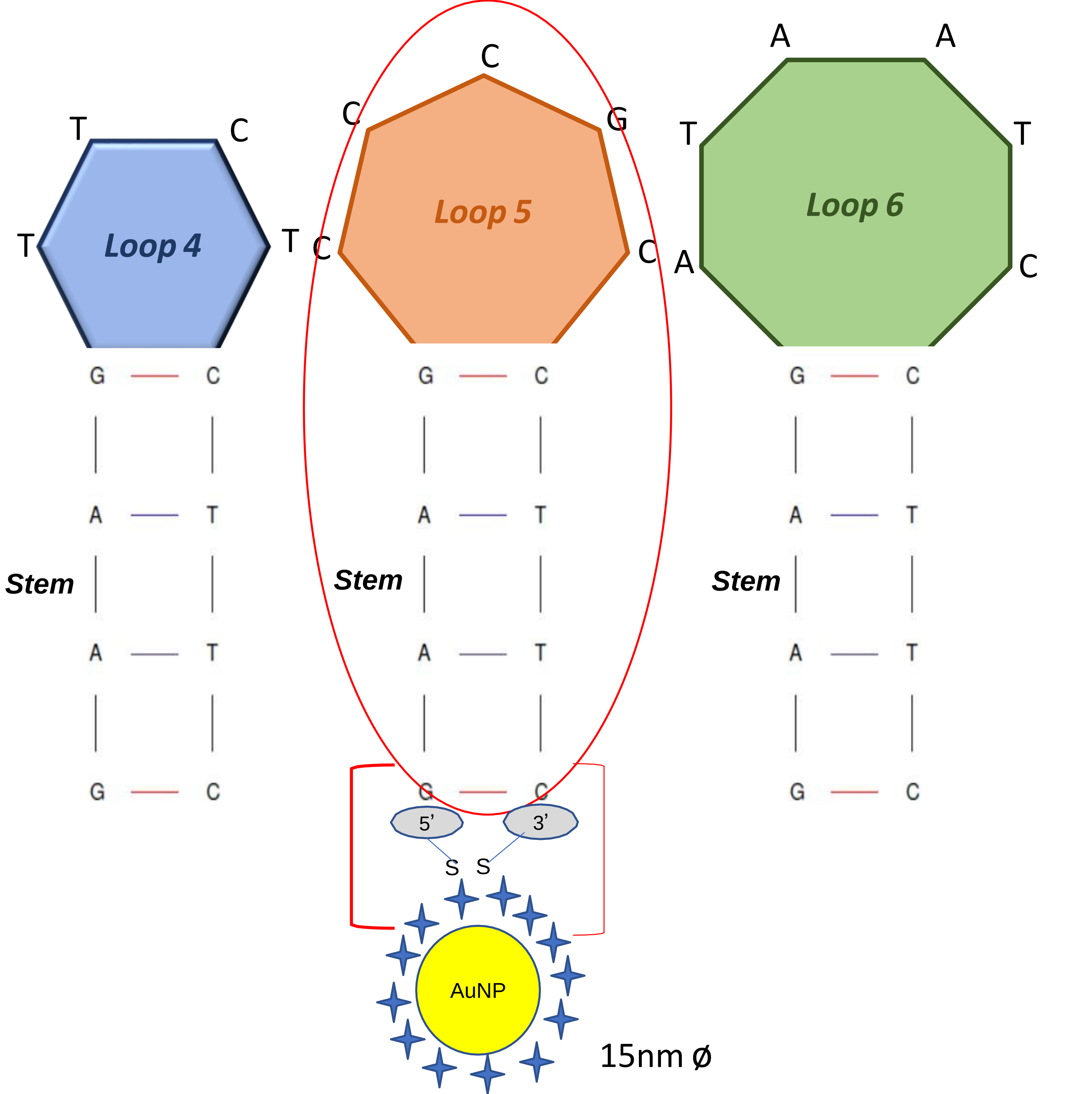
[Mascini, Marcello, et al. "Tailoring gas sensor arrays via the design of short peptides sequences as binding elements." *Biosensors and Bioelectronics* 93 (2017): 161-169.

UNITE

Hp-DNA

hpDNA has been used as molecular switch for optical and electrochemical sensing

- **The loop can be used as sensing elements also for VOCs**
- **A virtual screening of the entire library sequences of the loops is possible**
- **hpDNA can be easily bound to metal nanoparticles (AuNPs)**

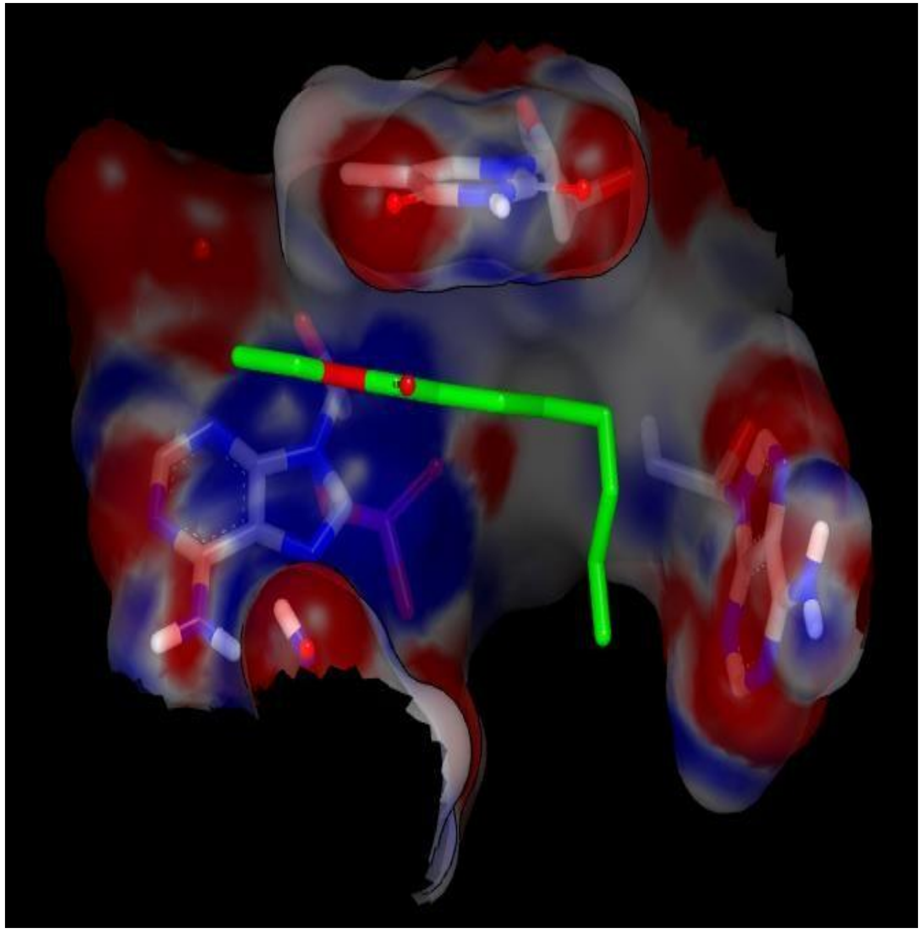


UNITE

Virtual screening of hp-DNA

Virtual screening procedure was aimed to test the virtual binding affinities of the hairpin loop versus different chemical classes:

- **Alcohols (14 molecules);**
- **Aldehydes (13 molecules);**
- **Esters (18 molecules);**
- **Ketones (5 molecules).**

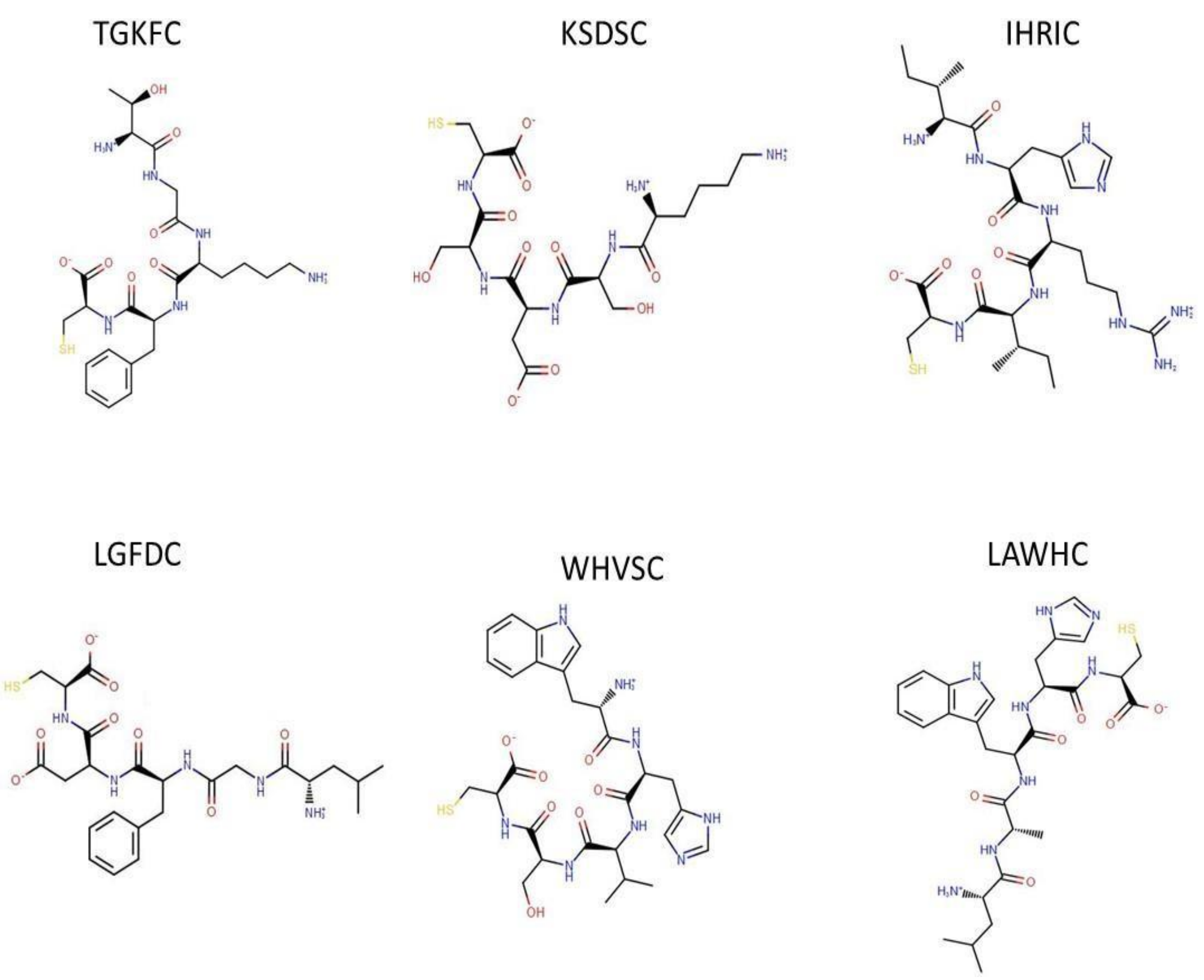


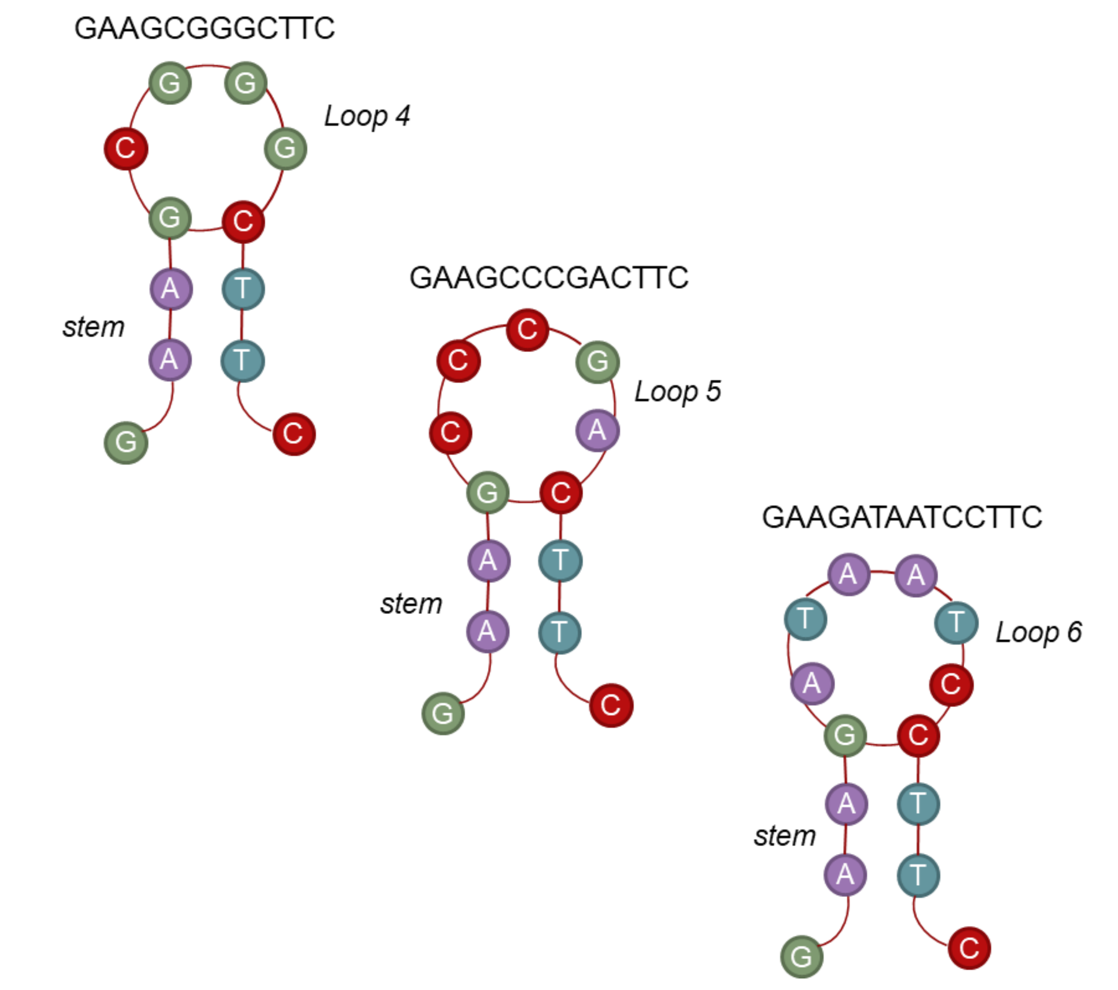
Molecular Modeling : octanal-ATAATC

OEDocking 3.0.0; VIDA version 4.1.1; OMEGA

Electronic nose sequences…

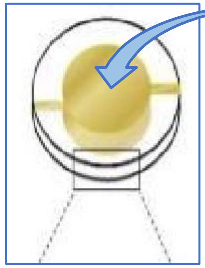
n=20





E-nose analysis

1



5 µL of the AuNPs-hpDNA and ZnO-Peptide suspension on each side of the QCM

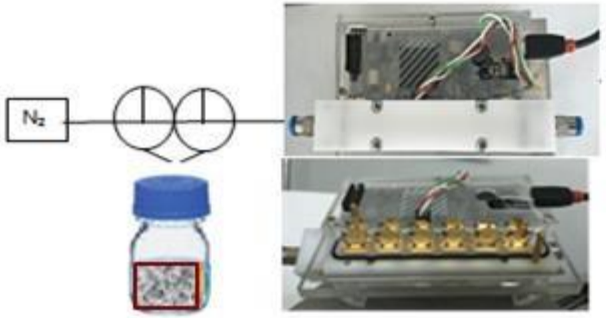
3

✓Aroma release in headspace of gas-tight bottle

5

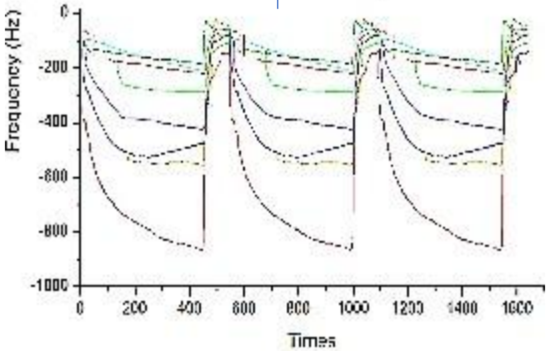
Measurement of aroma compounds; the frequency shift was taken as analitical signal

4



2

✓The samples was introduced in a gas-tight bottle (100 mL)



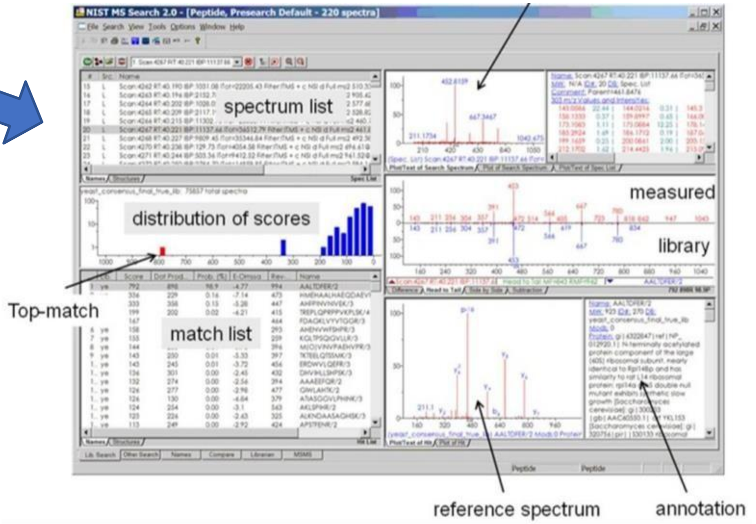
SPME-GC/MS analysis

UNITE UNIVERSITÀ DEGLI STUDI DI TERAMO

headspace analysis

Desorption

Nist library



Confirmed by Retention index…

Example…

Peak no.	RT[a] (min)	RI_{lit}[b]	RI_{cal}[c]	Identification[d]	Metabolite	MF[e]	m/z[f]	Similarity (%)	Peak area ($\times 10^6$ area units) $\pm$ RSD (%) DVB/CAR/PDMS[g]	PDMS[g]	CAR/PDMS[g]	PDMS/DVB[g]	PEG[g]	PA
1	1.42	-	908	MS, RI	Isoprene	C_5H_8	32, 67, 53	96	0.1 ± 7.8	-	0.4 ± 1.2	0.7 ± 1.5	-	-
2	3.92	1007	1016	MS, RI, ST	α-Pinene	$C_{10}H_{16}$	93, 77, 121	93	0.7 ± 9.7	1.0 ± 2.8	0.6 ± 2.9	0.5 ± 2.5	0.1 ± 3.1	0.02 ± 8.2
3	4.77	1075	1057	MS, RI	Camphene	$C_{10}H_{16}$	93, 121, 41	94	0.04 ± 8.7	0.2 ± 9.5	0.1 ± 8.5	0.3 ± 3.2	0.01 ± 5.5	-
4	5.73	1116	1107	MS, RI, ST	β-Pinene	$C_{10}H_{16}$	93, 41, 69	91	2.4 ± 1.2	5.8 ± 3.9	3.0 ± 3.2	3.2 ± 8.0	0.5 ± 2.7	0.1 ± 1.3
5	8.79	1145	1135	MS, RI, ST	β-Myrcene	$C_{10}H_{16}$	93, 69, 41	97	153.3 ± 1.1	191.1 ± 1.7	159.3 ± 1.9	126.7 ± 1.9	27.7 ± 2.5	7.6 ± 5.0
6	9.53	1180	1172	MS, RI, ST	Limonene	$C_{10}H_{16}$	68, 93, 79	93	1.3 ± 1.3	1.1 ± 5.0	1.2 ± 5.0	1.7 ± 7.6	0.3 ± 2.9	0.1 ± 2.1
7	10.01	1185	1182	MS, RI	β-Phellandrene	$C_{10}H_{16}$	93, 77, 136	95	1.1 ± 2.6	0.2 ± 6.8	0.9 ± 5.1	1.1 ± 1.0	-	-
8	11.64	1242	1246	MS, RI	*trans*-β-Ocimene	$C_{10}H_{16}$	93, 79, 41	89	0.1 ± 1.2	0.1 ± 7.4	0.1 ± 1.1	0.1 ± 2.4	0.01 ± 4.2	-
9	11.79	1262	1267	MS, RI, ST	α-Terpinene	$C_{10}H_{16}$	93, 136, 77	91	0.1 ± 1.4	0.1 ± 3.3	0.1 ± 2.6	0.1 ± 2.7	0.01 ± 3.5	-
10	12.48	1274	1279	MS, RI	*cis*-β-Ocimene	$C_{10}H_{16}$	93, 76, 41	92	2.1 ± 1.3	2.6 ± 3.2	2.2 ± 2.5	1.5 ± 2.5	0.2 ± 1.0	0.03 ± 1.3
11	13.15	-	1290	MS, RI, ST	o-Cymene	$C_{10}H_{14}$	119, 32, 134	95	0.1 ± 1.9	0.1 ± 2.7	0.1 ± 1.3	0.04 ± 1.3	0.01 ± 1.2	-
12	13.75	1284	1280	MS, RI	α-Terpinolene	$C_{10}H_{16}$	93, 121, 136	97	0.1 ± 3.4	0.1 ± 3.6	0.1 ± 1.0	0.1 ± 2.8	0.01 ± 1.1	-
13	22.88	1295	1305	MS, RI	Perillene	$C_{10}H_{14}O$	69, 81, 150	96	0.2 ± 1.5	0.2 ± 8.6	0.2 ± 2.9	0.2 ± 2.5	0.03 ± 2.3	-
14	26.07	1476	1481	MS, RI	Ylangene	$C_{15}H_{24}$	105, 119, 161	95	0.4 ± 2.0	0.2 ± 5.8	0.3 ± 2.0	0.2 ± 3.2	-	-
15	26,64	1480	1491	MS, RI	α-Cubebene	$C_{15}H_{24}$	161, 119, 105	91	1.2 ± 2.0	0.8 ± 1.7	0.8 ± 1.6	0.7 ± 3.5	0.1 ± 2.2	0.3 ± 1.6
16	33.62	1663	1621	MS, RI, ST	α-Humulene	$C_{15}H_{24}$	133, 93, 69	96	48.1 ± 7.5	52.8 ± 2.0	41.4 ± 1.5	36.8 ± 3.7	10.9 ± 2.6	3.1 ± 8.0
17	38.63	1657	1665	MS, RI, ST	β-Caryophyllene	$C_{15}H_{24}$	93, 80, 121	93	42.4 ± 4.1	21.3 ± 2.3	16.8 ± 1.9	15.4 ± 3.6	3.6 ± 2.5	1.0 ± 2.2
18	39.90	1681	1687	MS, RI	γ-Muurolene	$C_{15}H_{24}$	161, 105, 119	88	1.7 ± 2.7	1.3 ± 2.8	0.9 ± 1.8	0.8 ± 1.4	0.6 ± 3.3	0.1 ± 1.9
19	41.40	1566	1554	MS, RI	Methyl geranate	$C_{11}H_{18}O_2$	69, 41, 114	90	3.7 ± 1.1	3.1 ± 4.2	1.3 ± 3.1	2.3 ± 2.0	0.4 ± 2.8	0.1 ± 3.2
20	41.89	1724	1713	MS, RI, ST	α-Selinene	$C_{15}H_{24}$	189, 161, 93	92	0.8 ± 9.8	0.2 ± 2.3	0.2 ± 6.8	0.4 ± 4.1	0.2 ± 3.0	0.04 ± 2.3
21	42.50	-	1744	MS, RI	α-Muurolene	$C_{15}H_{24}$	105, 161, 93	89	0.3 ± 2.5	0.3 ± 1.8	0.2 ± 1.6	0.2 ± 4.1	0.1 ± 3.6	0.02 ± 1.4
22	44.59	1749	1740	MS, RI, ST	(+)-δ-Cadinene	$C_{15}H_{24}$	161, 134, 119	89	1.9 ± 2.2	1.6 ± 1.8	1.0 ±1.5	1.0 ± 4.2	0.4 ± 2.6	0.1 ± 1.0
23	45.88	-	1755	MS, RI, ST	Cubenene	$C_{15}H_{24}$	119, 105, 161	93	0.3 ± 5.4	0.2 ± 5.7	0.1 ± 1.2	0.2 ± 4.4	0.1 ± 3.8	0.01 ± 7.1
24	46.60	-	1769	MS, RI	Naphthalene H4,7DM 1R[h]	$C_{15}H_{24}$	105, 161, 91	96	0.2 ± 2.5	0.1 ± 2.1	0.1 ± 2.0	0.1 ± 4.7	0.1 ± 6.3	0.01 ± 9.8
25	48.27	-	1780	MS, RI	β-Fenchene	$C_{10}H_{16}$	79, 32, 67	95	0.1 ± 3.0	0.1 ± 4.6	0.02 ± 2.7	0.04 ± 5.2	0.01 ± 1.1	0.01 ± 1.0
26	49.30	1800	1789	MS, RI, ST	3-Carene	$C_{10}H_{16}$	69, 93, 41	98	0.9 ± 2.5	0.4 ± 1.1	0.3 ± 2.3	0.4 ± 5.0	0.3 ± 1.2	0.04 ± 8.0
27	51.68	1825	1835	MS, RI, ST	*cis*-Geraniol	$C_{10}H_{18}O$	69, 41, 93	92	0.2 ± 2.0	0.1 ± 3.9	0.1 ± 3.2	0.1 ± 2.0	0.1 ± 1.0	-
					Total peak area ($\times 10^6$)				**263.7**	**285.0**	**231.8**	**194.4**	**45.6**	**12.4**
					Average RSD (%)				**3.4**	**3.9**	**2.7**	**3.4**	**2.8**	**3.9**
					No. metabolite by fiber				**27**	**26**	**27**	**27**	**24**	**17**

a) Retention time (min).
b) Kovat's retention index reported in the literature for BP-20 capillary column or equivalents [53].
c) Kovat's retention index relative n-alkanes(C_8–C_{20}) on a BP-20 capillary column.

[4] Gallily, R., Yekhtin, Z. and Hanuš, L.O., 2018. The Anti-Inflammatory Properties of Terpenoids from Cannabis. Cannabis and cannabinoid research, 3(1), pp.282-290.

Headspace Volatile Evaluation of Carrot Samples Comparison of GC/MS and AuNPs-hpDNA-Based E-Nose

UNIVERSITA DEGLI STUDI DI TERAMO
UNITE

- Monitoring and control of vegetable ripening are important parameters in the food industry, since the maturation state during harvest, storage and distribution on the market defines the quality of the finished product;

- To prevent enzymatic reactions during processing, storage and thawing, the packaged carrots were blanched at 95 °C for 8 min in a water bath

- 3 g of blanched carrots were placed in 20 ml gas-tight vials and hermetically sealed with a gas-tight septum. A total of 24 vials were prepared for each temperature tested (-18 °C, 4 °C, 25 °C, 40 °C), in order to have three replicates (three different vials) for each day of measurement (1, 4, 8, 12, 19, 26 days). Thus, a total of 140 vials for E-nose and GC-MS have been analyzed. Each vial was used only once for either the GC-MS or E-nose measurement and the relative sample was discarded.

SPME-GC/MS

Volatile compounds	GC area (%) – Storage time (days) -18 °C					4°C						25 °C						40 °C			
	1	4	8	12	19	1	4	8	12	19	26	1	4	8	12	19	26	1	4	8	12
α-phellandrene	n.d	n.d	n.d	n.d	n.d	1	1	1	1	1	n.d	n.d**	1	n.d	n.d	1	n.d	7	1	n.d	n.d
β-phellandrene	2	1	2	1	1	3	3	2	1	4	1	n.d	3	1	1	2	n.d	n.d	n.d	n.d	n.d
terpinolene	n.d	n.d	1	1	0	1	1	1	n.d	1	n.d	n.d	1	n.d	n.d	1	n.d	n.d	n.d	n.d	n.d
α-pinene	14	9	12	12	10	14	12	14	14	18	8	12	7	12	11	15	2	n.d	10	15	5
(-) -β-pinene	3	2	3	3	3	3	3	3	3	3	2	2	3	2	2	3	1	n.d	n.d	n.d	2
β-pinene	3	2	3	2	6	5	6	3	3	5	1	2	6	1	1	4	n.d	5	3	3	2
Octanal	1	1	n.d	n.d	n.d	1	1	1	1	n.d	n.d	1	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
γ-terpinene	7	8	9	10	7	8	9	7	8	4	1	12	7	6	5	7	n.d	21	9	9	5
β-farnesene	1	1	1	1	1	1	1	1	1	n.d	1	1	1	1	1	1	2	n.d	n.d	n.d	n.d
α-caryophyllene	1	1	1	1	2	2	1	1	1	1	5	1	2	1	2	1	2	n.d	n.d	n.d	n.d
β-copaene	2	2	2	n.d	4	2	2	3	n.d	n.d	n.d	2	1	2	2	2	5	n.d	n.d	n.d	n.d
myristicin	1	1	1	1	2	1	1	1	1	1	5	2	1	2	n.d	1	4	n.d	n.d	n.d	n.d
elemicin	n.d	1	n.d	n.d	n.d	n.d	n.d	1	n.d	n.d	4	1	n.d	1	1	n.d	2	n.d	n.d	n.d	n.d
butane-2,3-diol	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	2	2	5	13	n.d	n.d	n.d	3
acetoin	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	9	3	6	15	5	3	5	6
ethanol	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	5	n.d	n.d	6
lactamide	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	4	11	16	7
3-methylbutan-1-ol	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	1	2	1	3	3	3

*(mean value of n=3 repetitions); **n.d.: not detected.

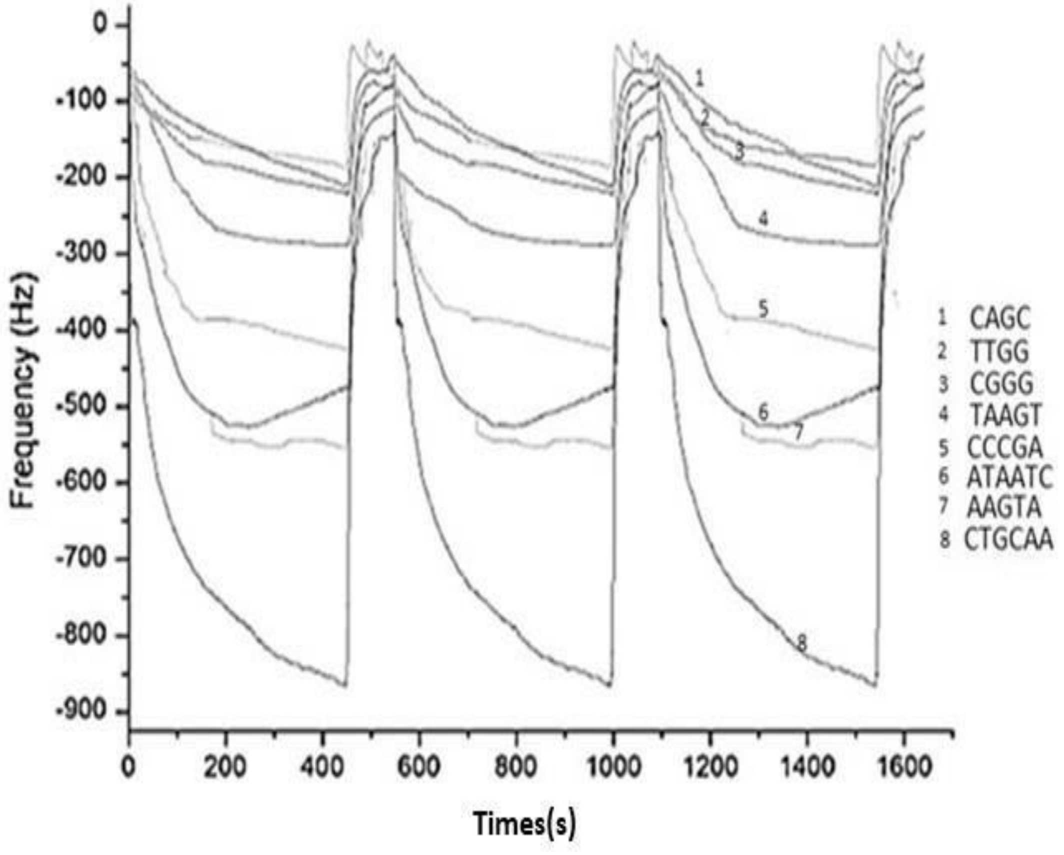
Results of the gas-chromatographic (GC) analysis of the headspace of carrots samples. Data are expressed as % of the total GC area*.

E-NOSE

UNIVERSITA DEGLI STUDI DI TERAMO
UNITE

Carrots Sample	CGGG	TTGG	CTGCAA	CAGC	TAAGT	AAGTA	ATAATC	CCCGA
25°C/1	145	199	314	187	409	566	686	147
4°C/1	118	221	132	155	417	468	564	107
-18°C/1	111	241	199	150	415	485	529	127
25°C/4	103	259	323	164	495	575	645	146
4°C/4	107	230	317	159	535	492	608	156
-18°C/4	101	208	244	155	577	513	603	165
25°C/8	148	228	339	237	544	462	787	216
4°C/8	130	204	179	174	480	632	701	180
-18°C/8	129	188	197	140	498	493	603	175
25°C/12	127	201	311	182	529	564	716	192
4°C/12	126	180	414	147	470	553	660	141
-18°C/12	105	205	403	166	602	495	664	148
25°C/19	87	131	120	100	374	515	565	135
4°C/19	86	257	301	145	483	696	600	160
-18°C/19	114	224	307	118	421	662	607	150
25°C/26	46	88	289	161	146	583	494	140
4°C/26	64	118	370	101	358	497	576	145
40°C/1	41	98	250	176	169	468	755	175
40°C/3	51	146	252	192	160	507	733	214
40°C/4	53	143	235	194	168	507	693	167
40°C/9	45	217	263	150	239	453	686	168

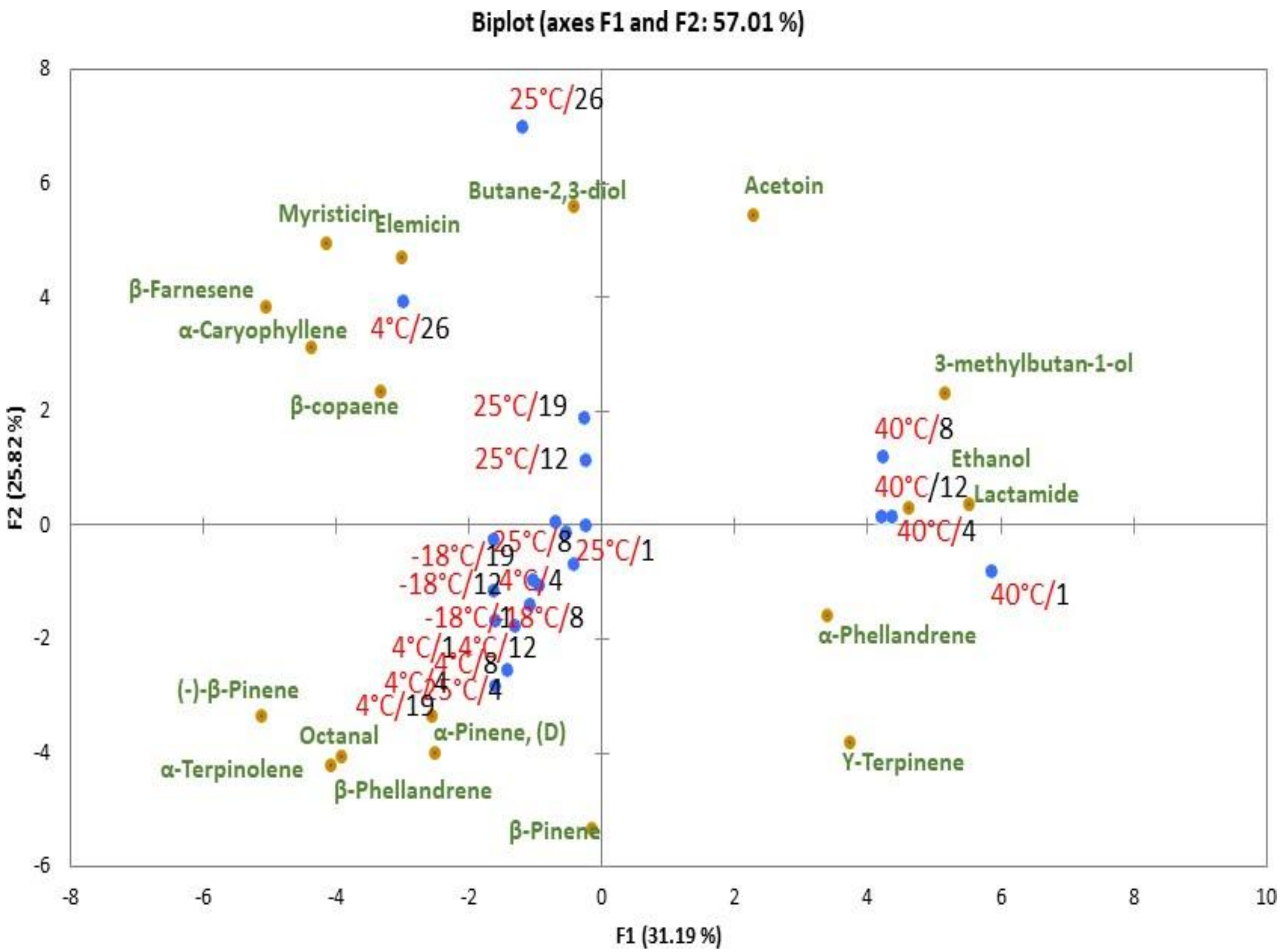
Frequency shift (Hz) response of the HpDNA sensors array for the carrots samples. The coefficient of variation calculated using three measurements taken in three different days was in all cases below 15%.



Frequency signal recorded with AuNPs-hpDNA testing carrots samples in triplicate

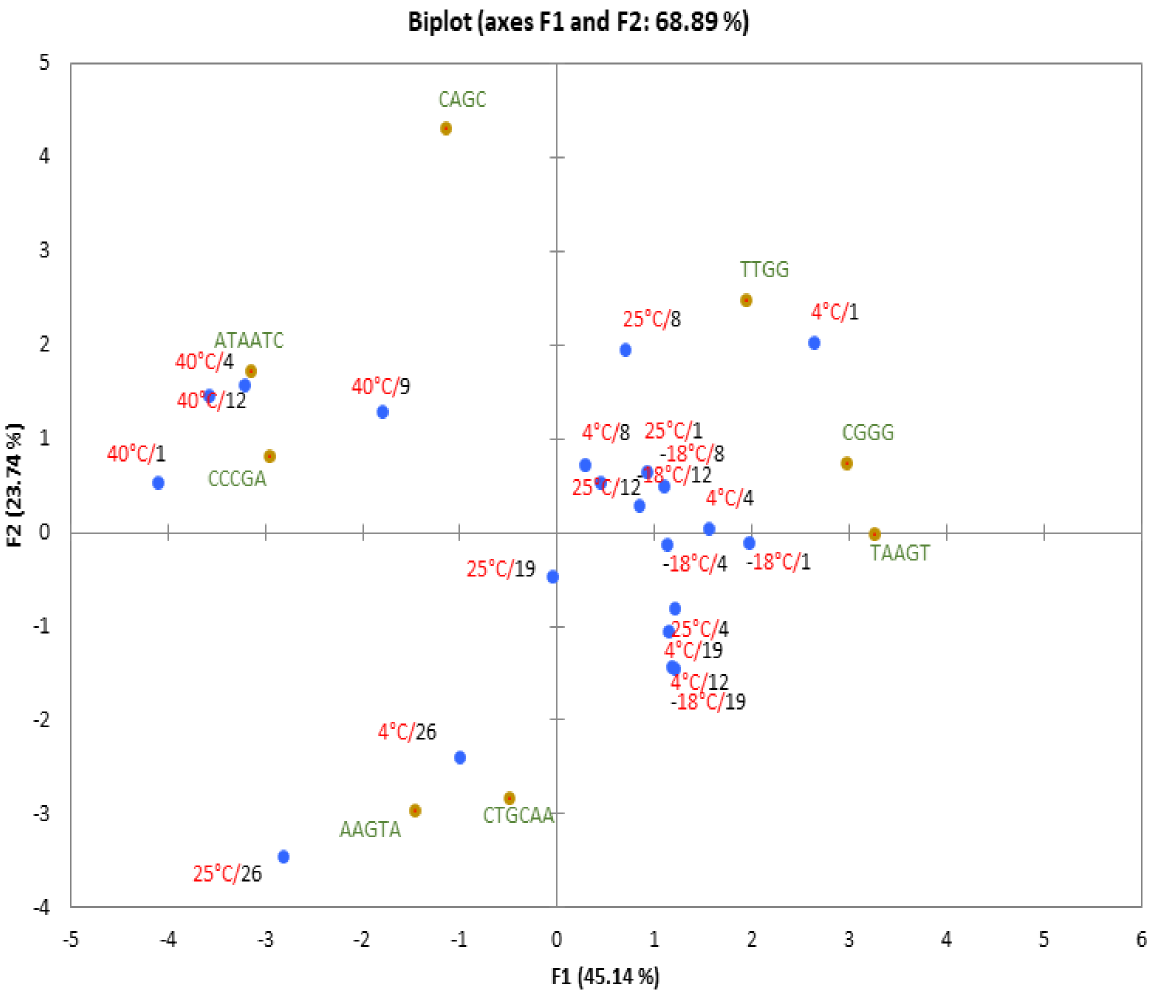
Results

GC-MS



PCA of the GC-MS/SPME response of carrot samples stored for different time at various temperature. Data are expressed in (Relative Abundance %) before PCA

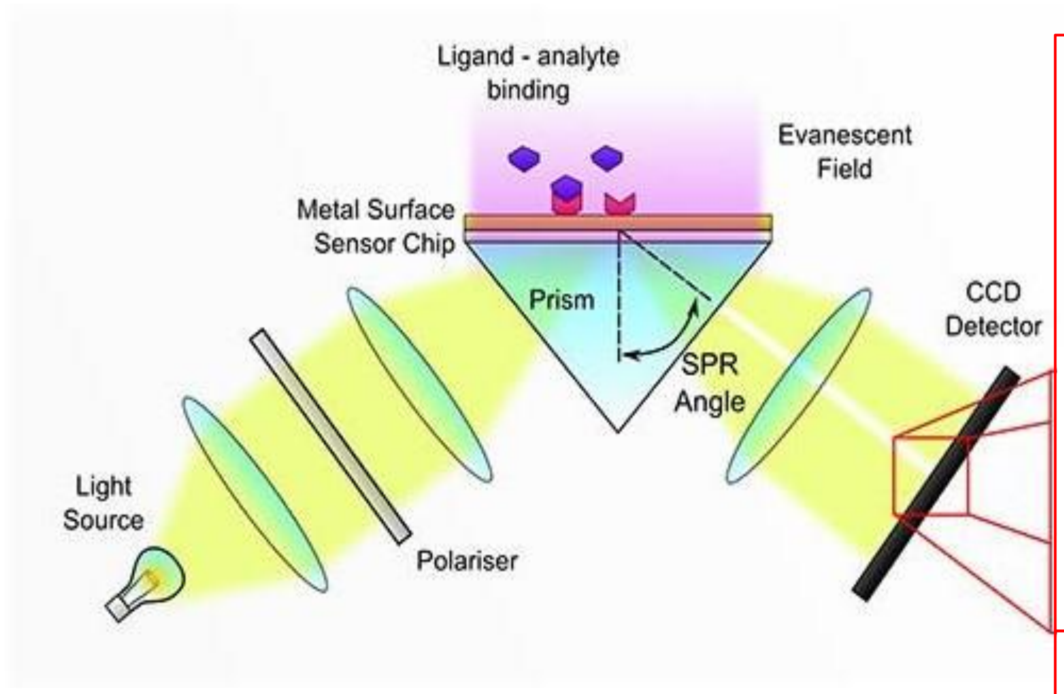
E-nose

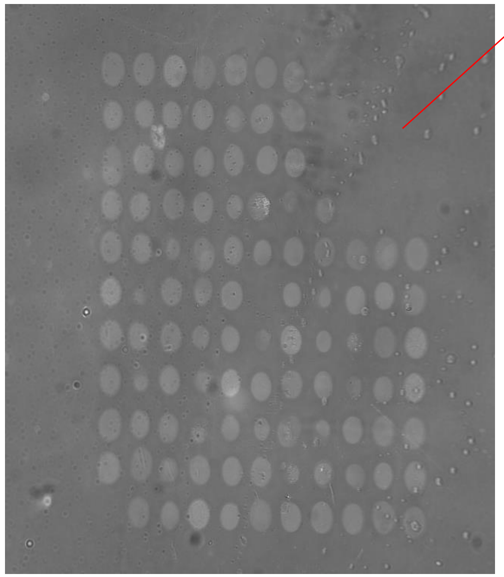


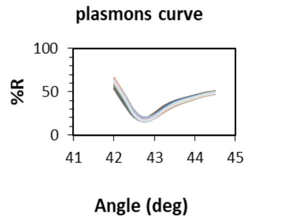
PCA biplot (scores and loadings) of the E-nose response to carrots samples. Data were normalized before PCA

Surface plasmon resonance imaging

home-made SPRI system



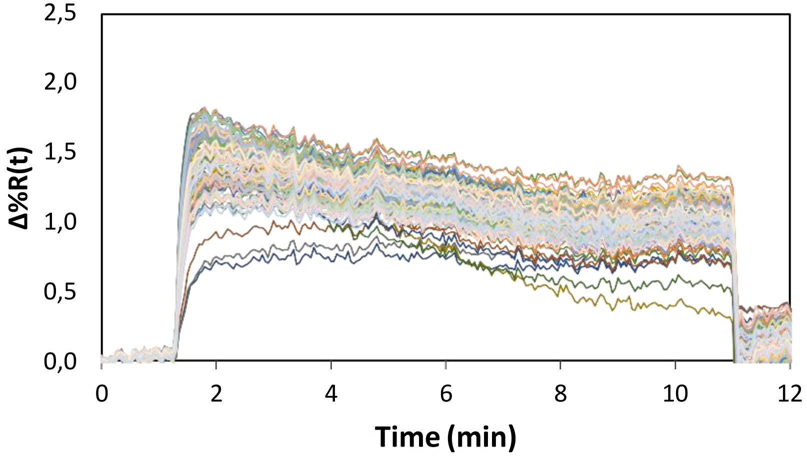


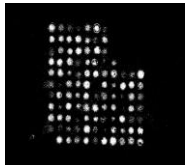


- *104 spot*
- *12 peptides at different concentration: 200µM and 400µM*
- *14 hpDNA: 16.8µM*
- *1.2 nL volume drop (≤1mm)*

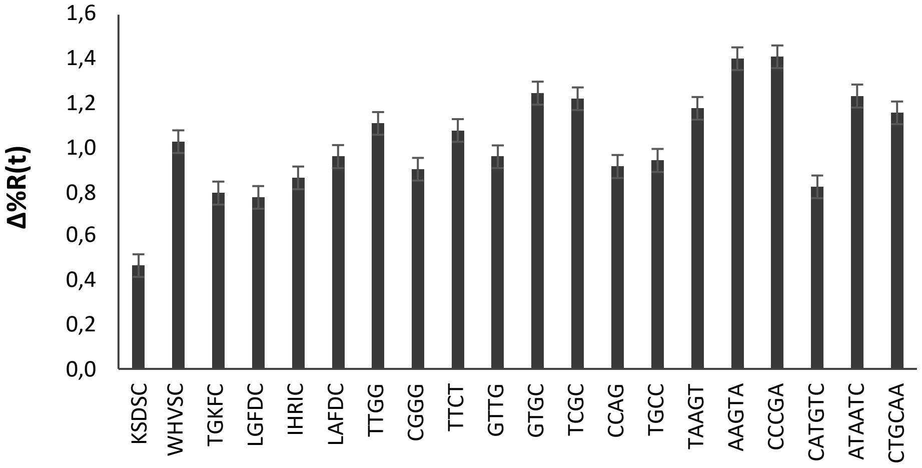
a)

1-butanol

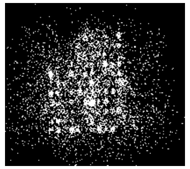


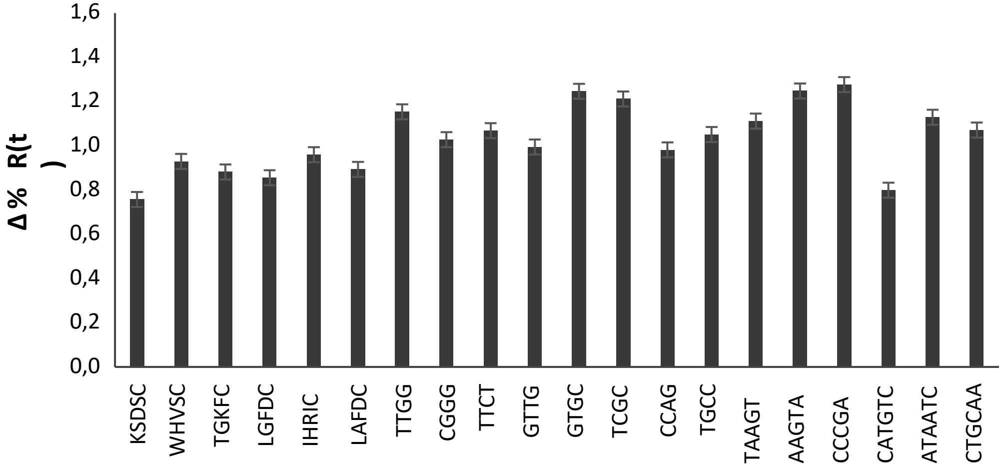


1-butanol



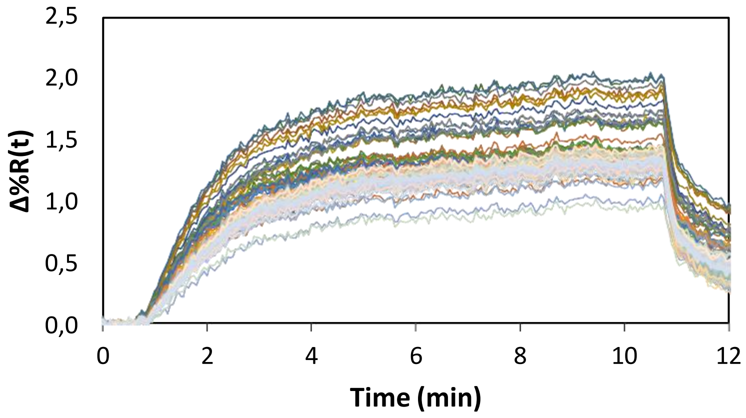
1-pentanol

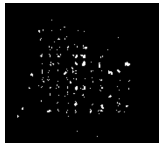




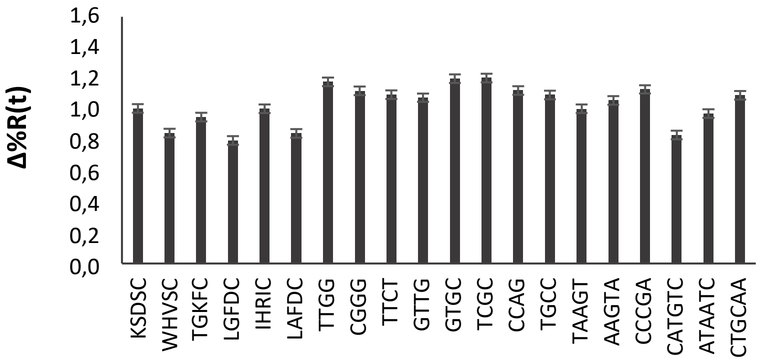
b)

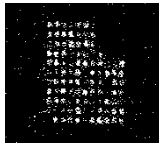
nonanal



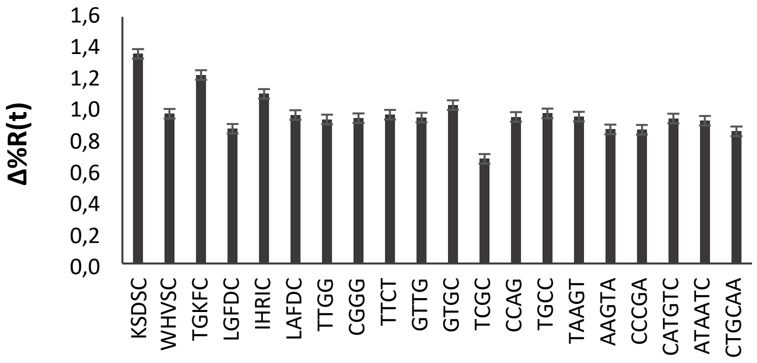


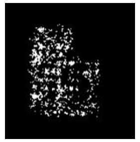
hexanal



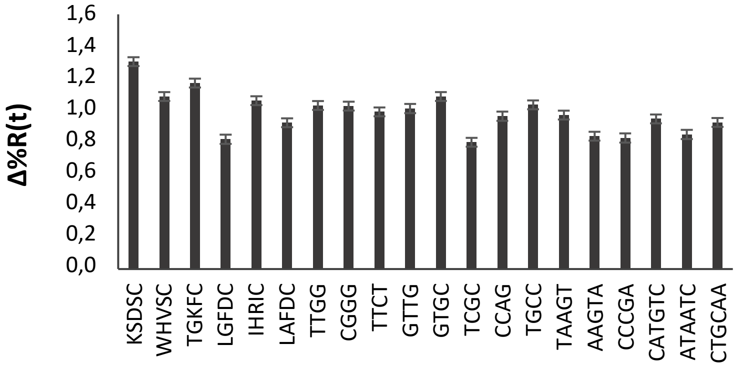


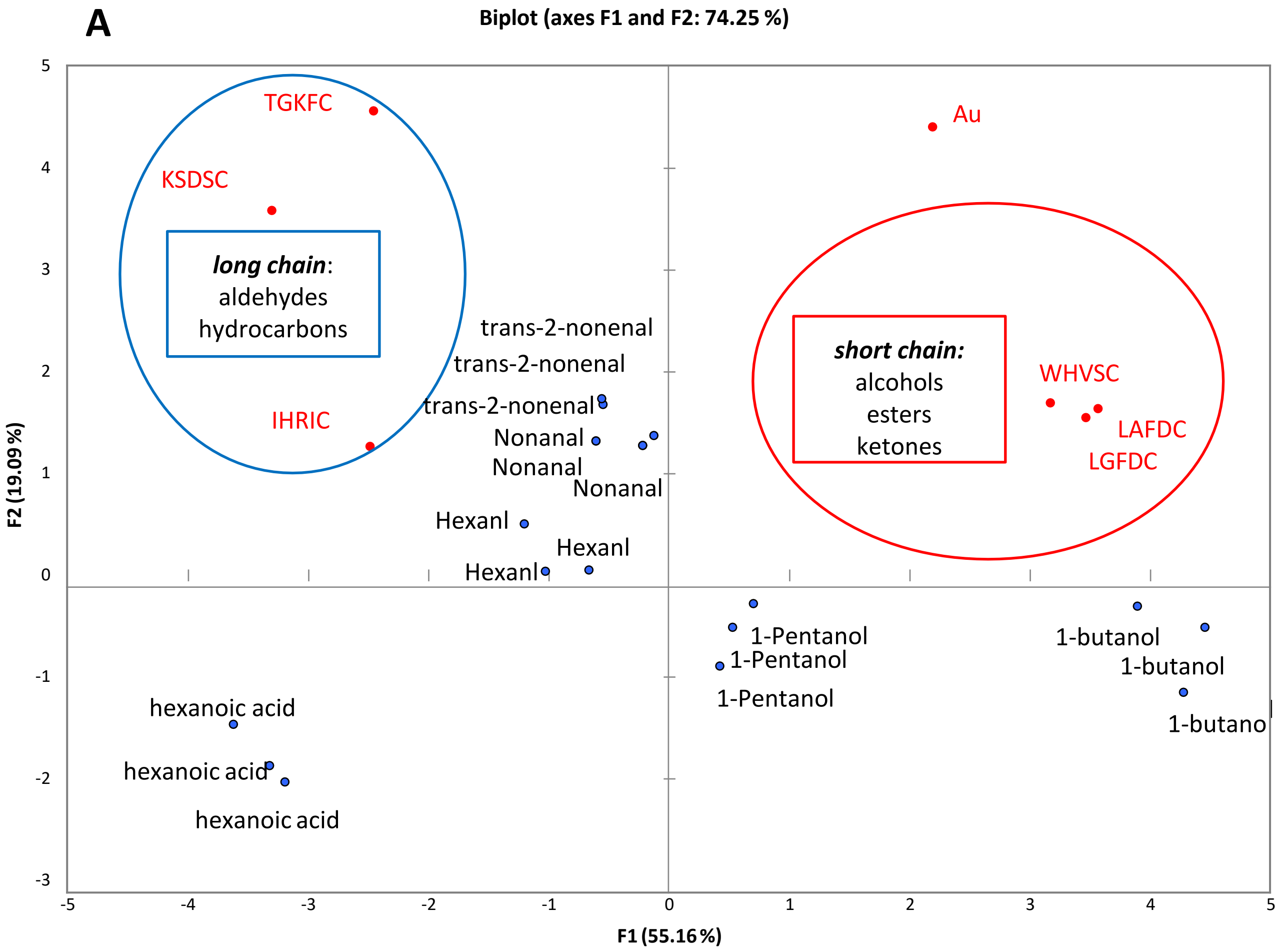
nonanal

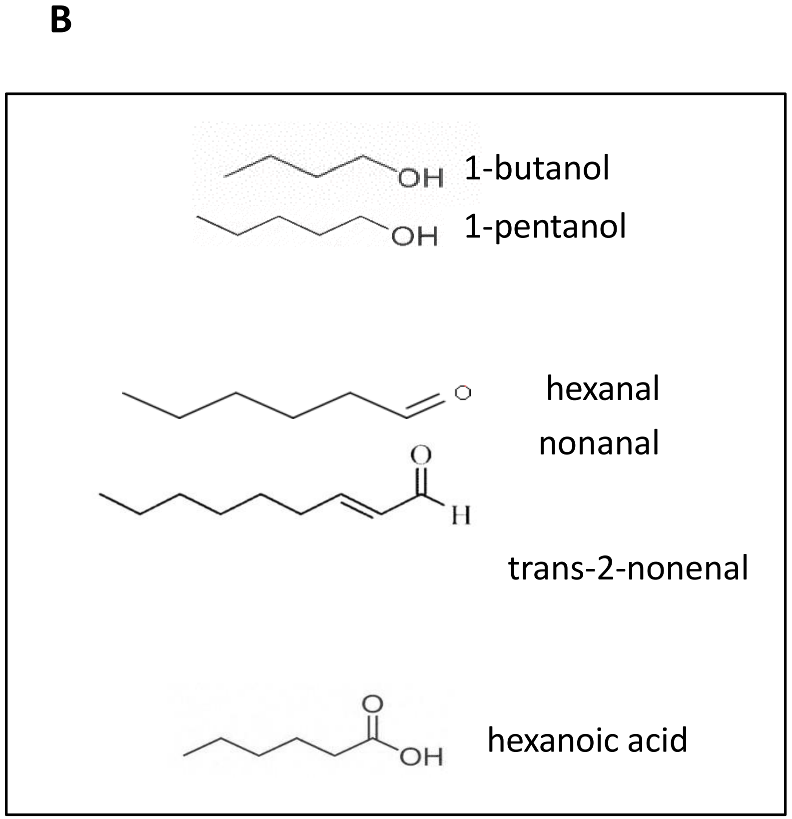




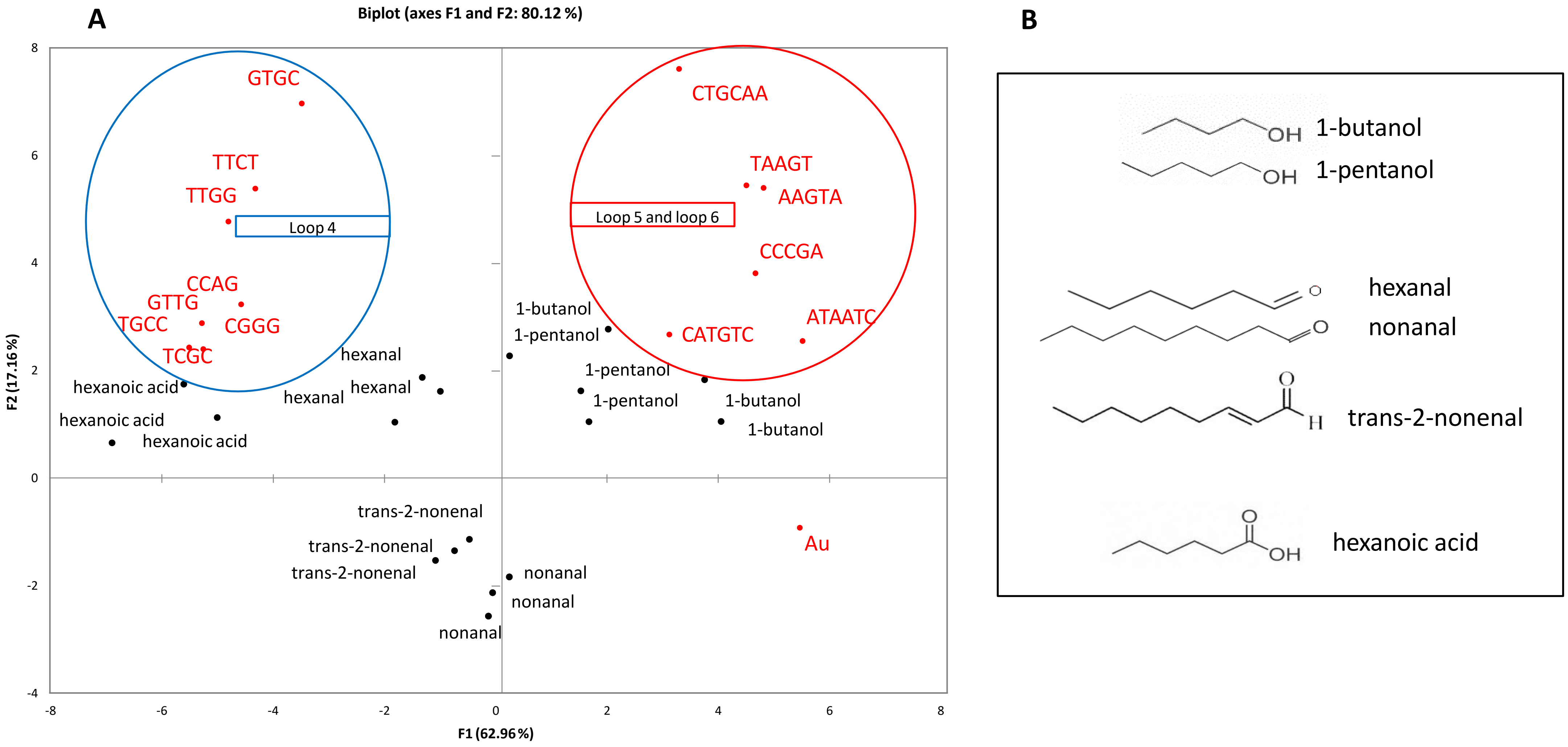
trans-2-nonenal



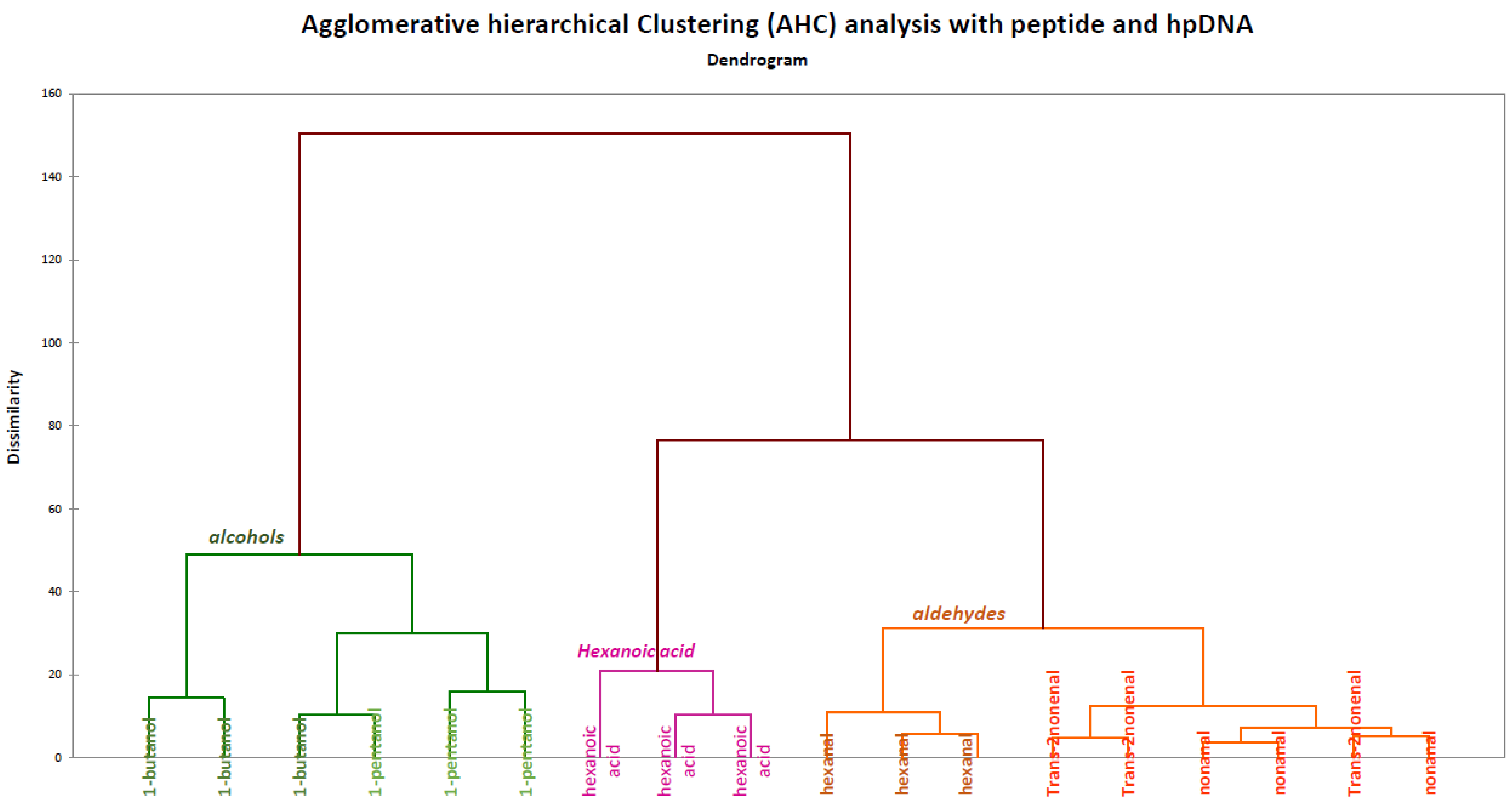




(A) PCA (*loading* and *score* plots) for the discrimination of different VOCs with different penta-peptides; **(B)** Explain the different chemical structures of VOCs tested: 1-butanol, 1-pentanol, hexanal, trans-2-nonenal, hexanoic acid



(A) PCA (*loading* and *score* plots) for the discrimination of different VOCs with different hpDNA; **(B)** Explain the different chemical structures of VOCs tested: 1-butanol, 1-pentanol, hexanal, trans-2-nonenal, hexanoic acid



Agglomerative hierarchical Clustering (AHC) analysis with peptide and hpDNA
Dendrogram
Dissimilarity
0
20
40
60
80
100
120
140
160
alcohols
Hexanoic acid
aldehydes
1-butanol
1-butanol
1-butanol
1-pentanol
1-pentanol
1-pentanol
hexanoic acid
hexanoic acid
hexanoic acid
hexanal
hexanal
hexanal
Trans-2-nonenal
Trans-2-nonenal
nonanal
nonanal
Trans-2-nonenal
nonanal

ELSEVIER

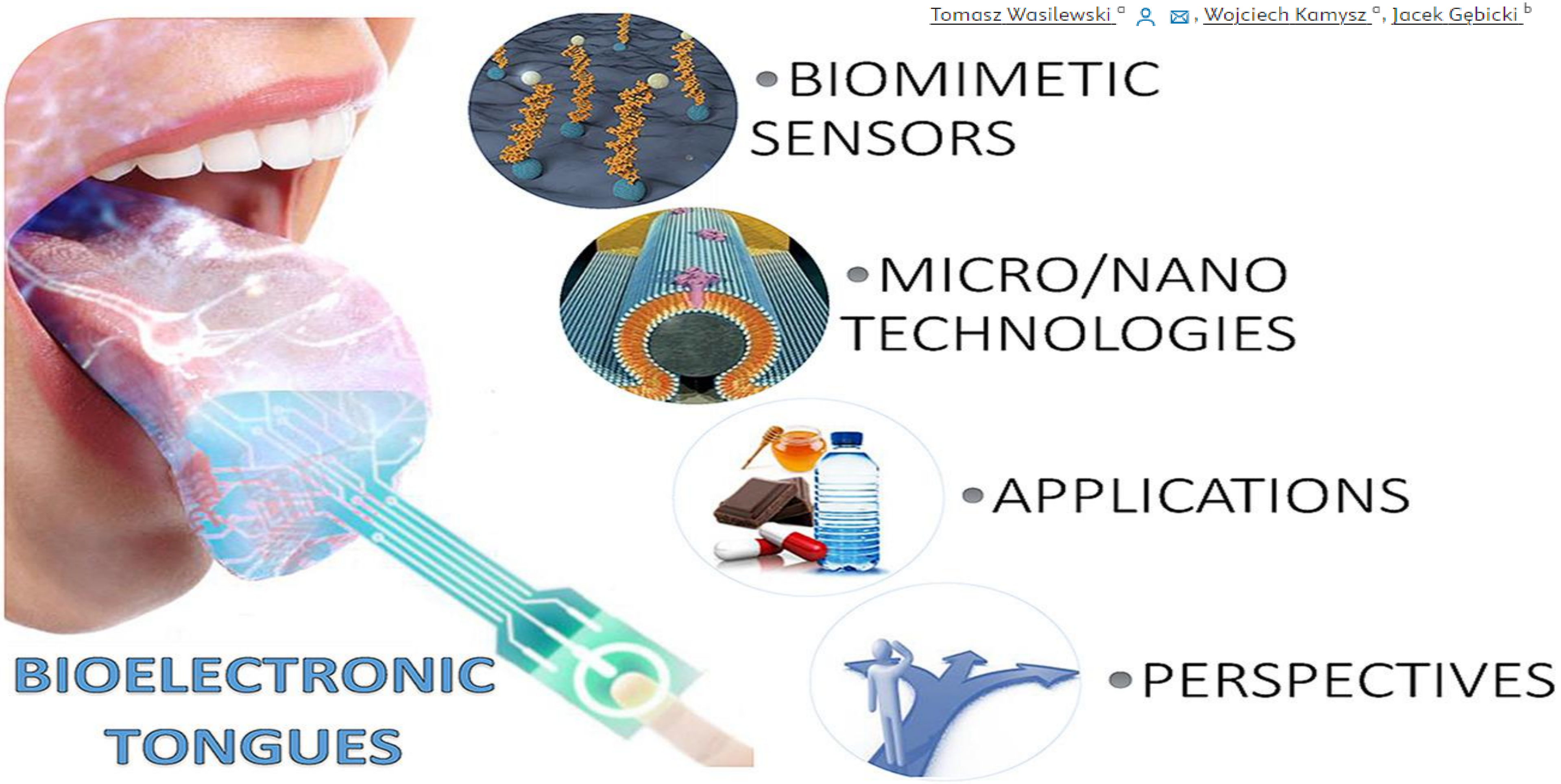
Biosensors and Bioelectronics

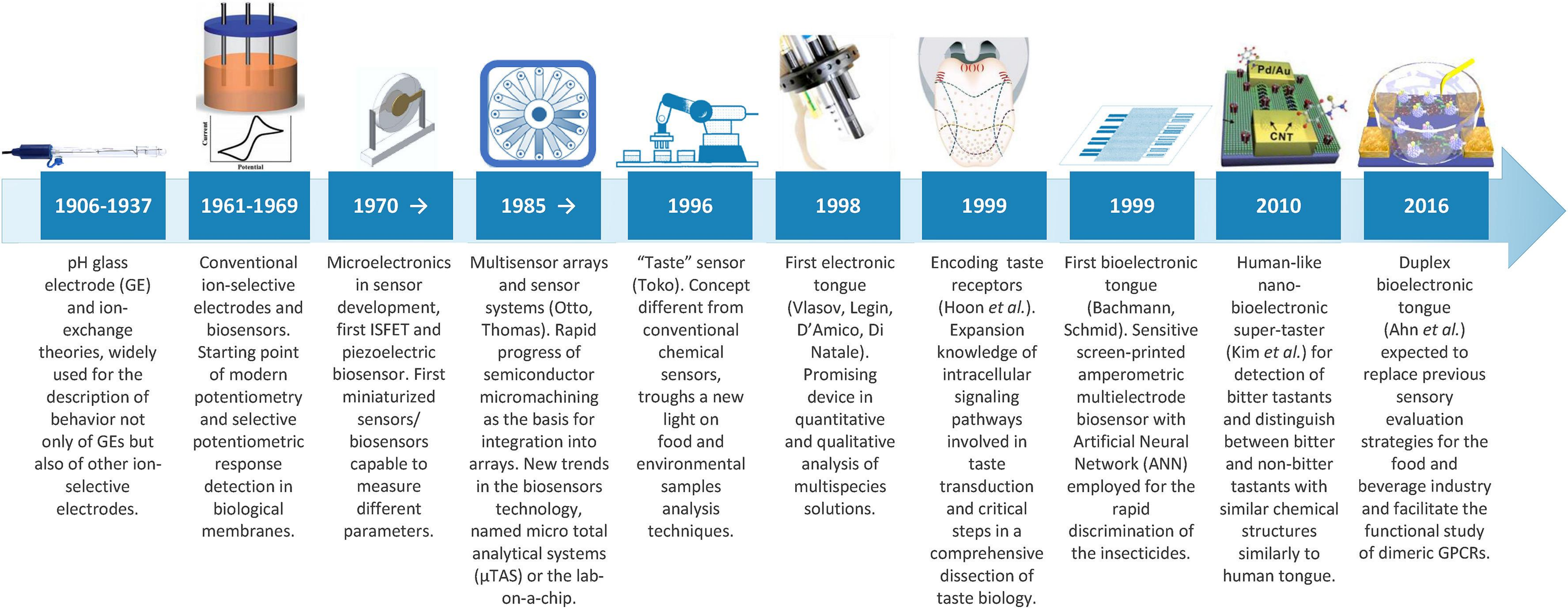
Volume 150, 15 February 2020, 111923

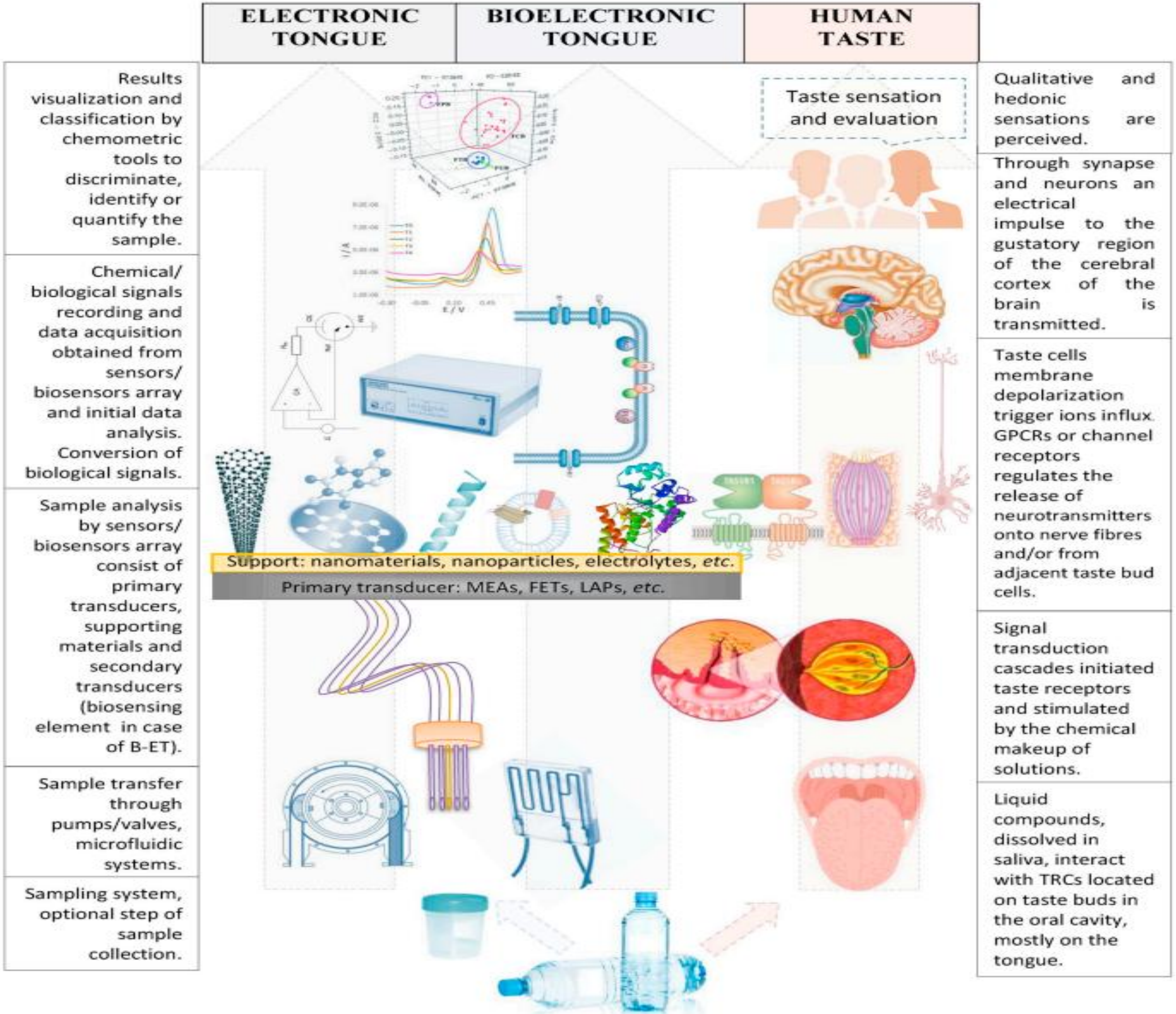
Go to Biosensors and Bioelectronics on ScienceDirect

Bioelectronic tongue: Current status and perspectives

Tomasz Wasilewski [a], Wojciech Kamysz [a], Jacek Gębicki [b]




Current
Potential
Pd/Au
CNT
1906-1937
pH glass electrode (GE) and ion-exchange theories, widely used for the description of behavior not only of GEs but also of other ion-selective electrodes.
1961-1969
Conventional ion-selective electrodes and biosensors. Starting point of modern potentiometry and selective potentiometric response detection in biological membranes.
1970 →
Microelectronics in sensor development, first ISFET and piezoelectric biosensor. First miniaturized sensors/ biosensors capable to measure different parameters.
1985 →
Multisensor arrays and sensor systems (Otto, Thomas). Rapid progress of semiconductor micromachining as the basis for integration into arrays. New trends in the biosensors technology, named micro total analytical systems (µTAS) or the lab-on-a-chip.
1996
“Taste” sensor (Toko). Concept different from conventional chemical sensors, troughs a new light on food and environmental samples analysis techniques.
1998
First electronic tongue (Vlasov, Legin, D’Amico, Di Natale). Promising device in quantitative and qualitative analysis of multispecies solutions.
1999
Encoding taste receptors (Hoon *et al.*). Expansion knowledge of intracellular signaling pathways involved in taste transduction and critical steps in a comprehensive dissection of taste biology.
1999
First bioelectronic tongue (Bachmann, Schmid). Sensitive screen-printed amperometric multielectrode biosensor with Artificial Neural Network (ANN) employed for the rapid discrimination of the insecticides.
2010
Human-like nano-bioelectronic super-taster (Kim *et al.*) for detection of bitter tastants and distinguish between bitter and non-bitter tastants with similar chemical structures similarly to human tongue.
2016
Duplex bioelectronic tongue (Ahn *et al.*) expected to replace previous sensory evaluation strategies for the food and beverage industry and facilitate the functional study of dimeric GPCRs.


ELECTRONIC TONGUE
BIOELECTRONIC TONGUE
HUMAN TASTE
Results visualization and classification by chemometric tools to discriminate, identify or quantify the sample.
Chemical/ biological signals recording and data acquisition obtained from sensors/ biosensors array and initial data analysis. Conversion of biological signals.
Sample analysis by sensors/ biosensors array consist of primary transducers, supporting materials and secondary transducers (biosensing element in case of B-ET).
Sample transfer through pumps/valves, microfluidic systems.
Sampling system, optional step of sample collection.
Support: nanomaterials, nanoparticles, electrolytes, etc.
Primary transducer: MEAs, FETs, LAPs, etc.
Taste sensation and evaluation
Qualitative and hedonic sensations are perceived.
Through synapse and neurons an electrical impulse to the gustatory region of the cerebral cortex of the brain is transmitted.
Taste cells membrane depolarization trigger ions influx. GPCRs or channel receptors regulates the release of neurotransmitters onto nerve fibres and/or from adjacent taste bud cells.
Signal transduction cascades initiated taste receptors and stimulated by the chemical makeup of solutions.
Liquid compounds, dissolved in saliva, interact with TRCs located on taste buds in the oral cavity, mostly on the tongue.

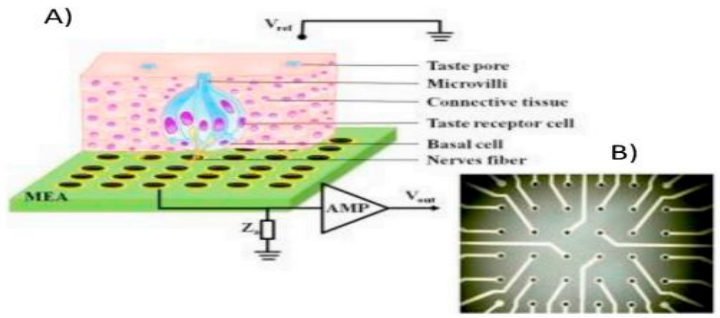


Fig. 4. Diagram of tissue-based B-ET (A) with the pattern of 36 channel MEA (B) and intact taste epithelium to record extracellular potentials from taste buds. Reproduced with permission from (Liu et al., 2013c).

MEA = microelectrode array

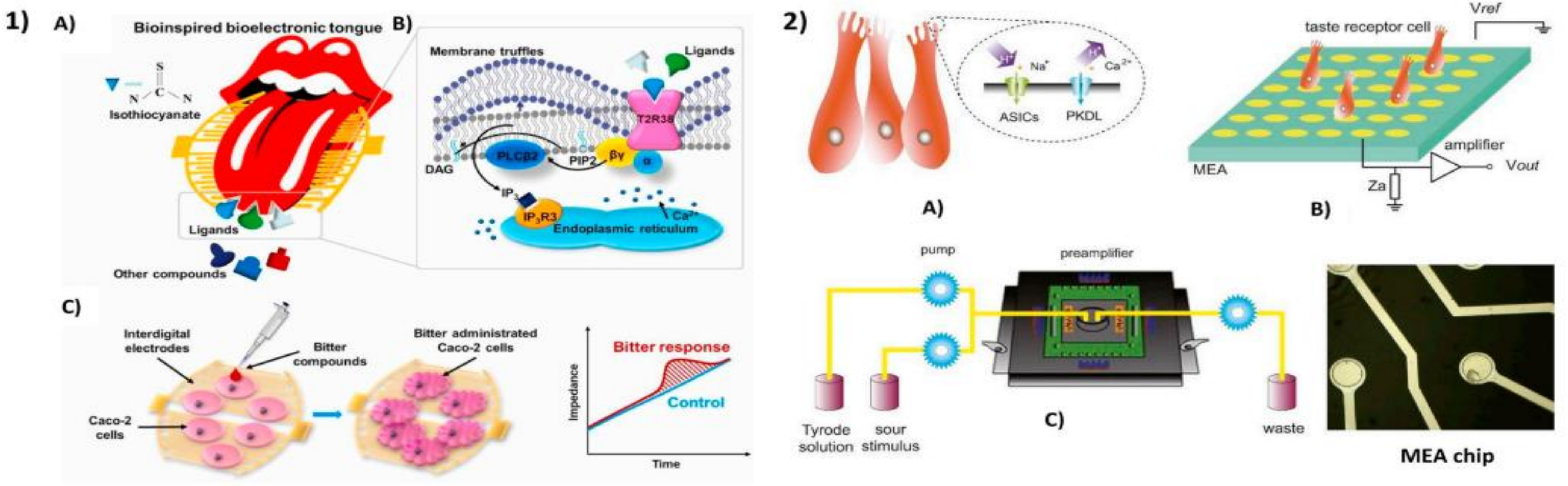


Fig. 5. Examples of cell-based biosensing instruments. (1) Schematic diagram showing cell-based bioinspired B-ET for iso-thiocyanates bitterness detection (A). Activation of the IP3/DAG pathway induces increased intracellular Ca2+ and membrane truffles (B), application of bitter compounds induces morphological and attachment changes as well as increases cell-electrode impedance (C). Copyright with permission from (Qin et al., 2019). (2) A biomimetic whole-cell based B-ET with MEA transduction: A switch for On- and Off-response of acid sensations. Acid-sensing ion channels and Polycystic-kidney disease-like channels (A) for acid sensing biosensor design (B) by extracellular electrophysiological recordings of taste cells. Copyright with permission from (W. Zhang et al., 2017).