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The influence of food composition and tag orientation on UHF RF IDentification

Abstract

Ultra-high frequency (UHF) radio frequency (RF) labelling is considered to be one of the most promising techniques for automatic identification through all food supply chain phases. However, the efficacy of RF IDentification (RFID) systems has proven critical for some food products.

In this paper the role of the composition and the temperature of the food product and of the mutual label-reader orientation on identification performances is investigated. For this purpose, basic food constituents, prepared as solutions (salts, sugars, organic acids and ethanol) at different concentrations and temperatures, were considered and then the identification results were compared to those obtained from whole food products.

The results show how the reading performances of UHF RFID systems are influenced by the considered parameters. The reading ranges for the identification of critical food products by UHF RFID systems can be estimated and then improved by considering the composition of the food product directly from the design phase.

Keywords: UHF RFID; Reading range; Temperature effect; Traceability; Food and beverage packaging; Tag detuning

Nomenclature

ε'	real part of permittivity
ε''	imaginary part of permittivity
σ	electrical conductivity [Sm^{-1}]
EPC	electronic product code
IC	integrated circuit
P_min	minimum power to activate the tag [mW]
TPO	transmitted power output [mW]
HDPE	high-density polyethylene
RF	radio frequency
RFID	radio frequency identification
UHF	ultra-high frequency

1. Introduction

As a type of automated data capture technology, Radio Frequency IDentification (RFID) is used to improve accuracy in inventory tracking, to accelerate picking and to reduce out of stock items as well as product shrinkage (Alfian et al., 2017; Bibi et al., 2017; Trebar et al., 2015). In spite of its being widely recognised as a viable tool for collecting and tracking information in different supply chains, RFID has not yet been widely used in the food and beverage industries.

The adoption of cheap label-type tags, operating in the ultra-high frequency (UHF) band, could overcome the obstacle of adopting expensive RFID systems due to high fixed costs (Sarac et al., 2010), allowing their integration in already available industry facilities, such as the automatic managing and sorting systems of packed products (Khan et al., 2018; Comba et al., 2013). The integration of UHF RFID-based traceability systems in the food and beverage industries represents a challenge due to the high water content in food composition and to the presence of special packaging such as aluminium foil boxes, glass bottles and jars (Barge et al., 2017a; Kumari et al., 2015). Moreover, the industrial environment can also affect RF devices

(Expósito and Cuiñas, 2013; Clarke and Tanprasert, 2005). The scouting of some possible solutions to improve the readability of critical products could help in identifying and in overcoming problems in the integration of UHF RFID systems in the food industry, warehouses and logistics (Alyahya et al., 2016; Lim et al., 2013). Indeed, the presence of even a few products that are difficult to track, when mixed with other products, excludes the possibility of adopting RF-based systems for traceability or logistics within the entire storage room. Knowledge of the limits of UHF RFID systems in identifying beverage bottles or other liquid food products will help to avoid failure in implementing the tracking systems.

Technical solutions to improve the readability of tags placed near liquid or metallic materials were investigated. In some cases, special inlays which use spacers (Deavours, 2010), foams, or innovative patented materials (Omni-ID) were proposed to improve tag reading ranges. These tags are often expensive and deeply modify the packaging shape.

Limited experimental work was done to assess the effect of different liquids in the vicinity of RFID tags attached to bottles. Efforts were made to avoid placing the tag on the bottle above the liquid level by attaching it on the neck, in the cap or in the cork (Gonçalves et al., 2014a), and some of those solutions, in the UHF or HF bands, were also patented and marketed. Other custom modified antennas were proposed by considering the effects on RFID readability when attached on bottles containing liquid with different dielectric properties (Sohrab et al., 2016; Gonçalves et al., 2014b; Björninen et al., 2011).

Although researchers have analysed the reading range reduction due to the vicinity of water, wine or chemical compounds, e.g. NaCl at different concentrations (Yu et al., 2015), there is still a necessity to investigate the effects of food products on the performance of UHF RFID systems.

In the UHF band, the propagation of electromagnetic waves is affected by objects in the environment that can cause absorption, detuning, reflections and impedance mismatch, usually leading to a dramatic reduction of the system's performance. Delivering enough power to the tag's integrated circuit (IC) was recognised as the major limiting factor in the correct interrogation and successful backscattering of a UHF transponder (Hodges et al., 2007; Nikitin et al., 2007). Both theoretical models and experimental approaches were adopted to calculate performance in terms of reading range and tag benchmarking (Yu et al., 2015). Methods for assessing the reading range, which are based on measuring the distance of the identified object till first detection (Barge et al., 2017b; Barge et al., 2014), are very time consuming, therefore different automatic data capture methods were developed (Adrion et al., 2017; Hodges et al., 2007).

For this reason, to study the reduction of the reading area caused by the vicinity of liquid food products (e.g. milk, cream, puree, tea, fruit juice, oil, spirits, etc.), the method for measuring the minimum Transmitted Power Output (TPO) required to activate the tag and to receive a response to the query at a fixed distance (Ukkonen and Sydnheimo, 2010; Nikitin et al., 2007) was adopted in this paper. Moreover, in order to verify the effect of food constituents on RF identification, solutions of chemical compounds were also tested, chosen among those which are often encountered in food products: salt, organic acids, sugars and alcohols. The orientation and temperature dependency on reading efficiency were evaluated with an automatic test system as well. The results will help to classify food items in categories by considering RFID readability degrees on the basis of the limits imposed by each chemical constituent. The availability of the obtained data allows UHF RFID systems to be optimised by evaluating possible methods to overcome the efficiency reduction of RF identification, such as changing the type of packaging material or shape, the adoption of an optimal orientation between the tag and the reader and the use of a different type of tag. The results of this paper may also be applied to the RF identification of liquids in other sectors (e.g. pharma or cosmetic products).

2. Materials and methods

2.1 Overview of the experimental trial design

The performance of a UHF passive tag, when attached to a flask filled with aqueous solutions at different permittivity or with food products, was determined at a fixed distance and by varying the emitted power. Tag readability was assessed as a function of four parameters: (1) chemical compound, (2) concentration of the chemical compound in the aqueous solution, (3) temperature of the solution in the range [4, 40] °C, and (4) orientation of the tag with respect to the UHF RFID reader antenna. The minimum TPO required to activate the tag and to successfully acquire its Electronic Product Code number (EPC global Inc., 2005) was recorded and herein indicated as P_min [mW]. To assess the effect of the food on tag readability, the flask was then filled with different food products and the effect of both temperature and orientation on the UHF tag was also assessed. Experimental tests on food products were conducted at 4°C, which is the recommended storage temperature for chilled products (skimmed milk, cream, etc.), and at 20°C, standard shelf temperature at which foods may be stored (oil, spirit, tea and soup).

2.2 Description of the test bench

The test bench (Fig. 1a) was designed to minimise any electromagnetic (EM) field attenuation and/or wave reflection interference. Specifically, the entire frame of the test bench was made of wooden planks, wooden plugs and glue. The wooden frame was used to bear a polystyrene slab that held the supports for the antenna and for the HDPE (High-Density Polyethylene) flask (Fig. 1b). The HDPE material, having a dielectric permittivity with a real part (ε^') of about 2.35 and an imaginary part (ε^'') of about 5·10-4, was chosen as it interferes minimally with the electromagnetic field (Mujal-Rosas et al., 2015). The adopted HDPE flask, with a cylindrical shape (74 mm diameter, 160 mm height and 1 mm thickness), was firstly filled with a 500 mL aqueous solution of four different analytical-grade chemical compounds and then with food products. The UHF passive tag was vertically attached to the external surface of the HDPE flask (Fig. 1b). A LabID UH105 tag (91x18 mm) with an Impinj Monza 5 integrated circuit (nominal sensitivity of 0.01 mW) was chosen on the basis of its good performance in the presence of liquids (Barge et al., 2017a).

To automate data acquisition for each rotation angle, the flask was placed on the polystyrene support and connected by means of a shaft to a stepping motor installed at the bottom of the wooden frame (Fig. 1a). The driver (Pololu Mod. MD20B) of the stepping motor was controlled by an Arduino MINI module. The rotation step of the motor was set to 7.2° in order to obtain 50 different positions of the tag per full rotation angle (360°) of the flask.

A commercial UHF RFID standalone reader (Caen R4300P) was connected to a linear polarised antenna (Caen RFID, model Wantenna X007, 8 dBi gain) operating at 866.6 MHz central frequency. The stepping motor and UHF RFID reader were controlled by a custom C# software, which commanded both the tag interrogation and the rotation of the HDPE flask. The distance between the reader antenna and the vertical axis of the HDPE flask was fixed at 500 mm to operate at low power levels, thus minimising the effect of the external environment. The antennas of the reader and of the UHF passive tag were aligned to minimise polarisation loss.

2.3 Sample preparation and analysis

Four substances were selected as representative of food and beverage composition: (1) sodium chloride, (2) citric acid, (3) sucrose and (4) ethanol. The solutions were prepared with analytical grade compounds in deionised water at five different concentrations (% w/w): 0.1%, 0.2%, 0.5%, 1% and 2% for sodium chloride, 1%, 2%, 4%, 5%, and 10% for citric acid, 1%, 5%, 10%, 20% and 40% for sucrose and 2%, 5%, 10%, 20%, 40% and 100% for ethanol. Retail food products were used to assess the effects of milk, milk cream, sweetened tea, grappa (a typical Italian spirit), sunflower oil and artichoke soup on tag readability. The food products nutrition facts, declared on the labels and complying with Regulation 1169/2011 (European Commission, 2011), are reported in Table 1.

The electrical conductivity of both solutions and food products was determined at different temperatures in the range [4, 40] °C by a conductivity meter (Crison Instruments Micro CM 2201) equipped with a platinum conductivity cell (Crison 5292) and a temperature sensor. The temperature compensation feature of the conductivity meter was disabled; temperature and electrical conductivities were recorded at 1°C temperature steps.

2.4 Data collection method

The measurements were conducted outdoors by keeping the system as far as possible from any metal object or RF reflective material. The reader started by sending the EPC Gen2 (EPC Global Inc., 2005) interrogation signal to the tag when it was facing the reader antenna (0° rotation around the vertical axis). Reader TPO was then progressively increased until the tag identification code was successfully acquired by the reader. The TPO threshold for tag activation was then measured and indicated as P_min. Once the tag ID was acquired, the control system allowed the motor to rotate to the following step. The process was repeated by measuring P_min for the full rotation angle. When the tag was not acquired, power ramping stopped at 2 W, which was stated as the higher TPO limit for the feasibility of an industrial system implementation. When needed, RF attenuators (3, 10 and 20 dB) were used to obtain P_min values in the reader operating range.

To verify the effects of the flask material, P_min was firstly measured when the HDPE flask was empty, then the flask was filled with deionised water, chemical compounds solutions and food products. The solutions and food products temperature was progressively raised and measured at the beginning and at the end of data acquisition for a full rotation angle. During data acquisition, the HDPE flask was covered with a polystyrene box to avoid the influence of direct solar radiation on the tag.

3. Results

3.1 Temperature effect on electrical conductivity

The temperature effect on electrical conductivity (σ) of citric acid, sodium chloride, sucrose and ethanol solutions at different concentrations was tested and compared to those of the considered food samples (Fig. 2). Conductivity of both the tested solutions and the considered food products resulted to be significantly correlated to the temperature.

In the case of ionic molecules such as sodium chloride, an increment in concentration determines a very high conductivity enhancement (Fig. 2b). Citric acid (Fig. 2a), with its three anions, behaves in water like a weaker electrolyte (Apelblat and Barthel, 1991). Since sucrose solutions have low conductivity (Fig. 2c), a conductivity increase was not observed for sucrose concentrations higher than 20%. Pure ethanol (Fig. 2d) is highly resistive and its addition to water reduces the σ of the solution. However, an increment in electrical conductivity was not found to be proportional to the ethanol concentration (Personna et al., 2013). This could be due to the complexity of the ethanol/water molecules chemical interaction and their configuration at different concentrations (Kitahara et al., 2005).

Fig. 2e shows the conductivity of food products as a function of temperature. The artichoke soup turned out to be the food with the highest conductivity. This could be due to the presence of 0.68% salt (Table 1).

Indeed, the regression line for artichoke soup is comparable to the results obtained for sodium chloride solutions at 0.5% and 1%. The same similarities were observed for skimmed milk (0.13% salt) and milk cream (0.08% salt). Sunflower oil and grappa were found to have very low conductivities.

3.2 Analysis of food composition on UHF tag readability

Polar charts, which report the P_min values recorded at each rotation step, are shown in Figs. 3 to 5 and 7 to 9. For easiness of explanation, out of range values (P_min > 2 W) were not reported on the polar charts. This is the reason why the values on some of the radii of the charts are missing. Two side zones, where tag identification is very critical, were detected in most of the polar charts.

As it can be seen in most of the polar charts, the curve shapes turned out to be asymmetric. This can be ascribed to the antenna shape which is not symmetrical (see Fig. 1b). In this paper, the tag orientation as depicted in Fig. 1b was named “position A” while the orientation named “Position B” was obtained by a 180° plane rotation around the IC (Integrated Circuit) with the microchip and the loop on the right side. A test, conducted with a 0.2% sodium chloride solution (Fig. 3a), clearly demonstrates that the asymmetry of the resulting polar charts is due to the shape of the tag antenna. The experimental tests were all conducted with the tag in position A.

The flask material (HDPE) had negligible effects on the power level for tag activation as, with an empty flask, P_min was lower than 3 mW for all orientations.

In the experimentation tests, when the flask was filled with deionised water (Fig. 3b), it was always possible to receive the backscattered signal when the tag was in the rear position (from 100° to 270° rotation angle). On the contrary, in frontal position (when the reading antenna was frontally facing the flask, from -30° to 50°), the P_min increased with the temperature till 20 °C. In particular, it was not possible to have a response from the tag in frontal position at 15 °C and 20 °C (orange and yellow lines in Fig. 3b). At 30 °C, the tag was readable in frontal as well as in rear position, with blind spots on the flask sides (Fig. 3b, red line).

3.2.1 Effect of food constituents

Regarding the citric acid and sodium chloride solutions, at the two lower concentrations (0.1% and 0.2% for NaCl and 1% and 2% for citric acid), tag detection was possible in both the frontal and rear positions (Figs. 4a and 4b; Figs. 5a and 5b). Raising the concentration for both compounds, P_min with the tag in the rear side of the flask increases considerably (Figs. 4c and 4d; Figs. 5c and 5d). In both cases, a temperature increase limits the reading range. In the case of sodium chloride at 0.5%, the tag was readable only in the range [4, 15] °C (Fig. 5c); when the concentration exceeded 0.5%, the tag was not readable in the rear position in the considered temperature range (Fig. 5d). This could be due to the fact that, in water solutions, when ions interact with dipoles, the real part of the complex number representing permittivity (ε^') decreases with increasing concentrations (Levy et al., 2012). Ionic conduction due to salt addition has a large influence on ε^'' (the imaginary part of permittivity) that is proportional to the power dissipation into the medium (Venkatesh and Raghavan, 2004). The effect of the electrical conductivity of the solution on P_min, when the tag was in rear position (orientation angle 180°), was therefore analysed. An exponential correlation between P_min and the electrical conductivity was observed for citric acid and sodium chloride with a good degree of approximation (Fig. 6).

In the case of sucrose solutions at 1% and 5% concentrations (Figs. 7a and 7b) and ethanol/water mixtures at 5% concentration (Fig. 8a), tag readability was found to be in the frontal position. For sucrose and ethanol at concentrations higher than 10% (Figs. 7c and 7d; Figs. 8c and 8d), the optimal reading zone was detected when the tag was placed in the frontal position. For sucrose at 20% and ethanol at 10% the tag was correctly detected both in frontal and in rear position at all the considered temperatures.

The results showed that tag readability is very critical or even null in many cases when the tag is not optimally orientated (i.e. tag near to 90° or 270°, where the energy harvesting area of the antenna is almost aligned to the propagation direction of the field). However, the amplitude of the shape of these lateral critical zones does not depend only on the mutual orientation of the tag and of the antenna but it is also highly influenced by the chemical and physical properties of the liquid that is interposed between the tag and the antenna.

3.2.2 Effect of food products

In the polar charts of Fig. 9, P_min values registered when the flask was filled with food products at 4 °C or 20 °C are shown.

Food matrices are very complex and the effect on the dielectric properties of each of the constituents is not predictable a priori. For example, the influence of salts depends on how they are bound or restricted by the other food components (Jha et al., 2011). However, similarities between pure chemical solutions and food products were detected. For example, while in frontal position P_min is low both for skimmed milk and milk cream (Figs. 9a and 9b), in rear position good readability was registered for milk cream while for skimmed milk the diagrams are similar to those observed for highly polar solutions (e.g. sodium chloride at 0.5% or citric acid at 5%). This could be due to the fact that milk cream contains a high percentage of fats, which are apolar compounds, while in skimmed milk, salt and water content could have caused a reduction of readability. The presence of skimmed milk could also have contributed to power dissipation as it is proven to enhance the dielectric loss factor at 915 MHz (Zhu et al., 2015). Therefore, for skimmed milk plastic bottles, the tag rotation with respect to the antenna should be chosen from 0° to 100° and from 280° to 360° to identify UHF RFID. In fact, in rear position, P_min is higher and two no-reading zones at 120-160 and 220-270 degrees rotation angles are also present. Readability was found to decrease by raising the temperature to 20 °C.

Both for sweetened tea (Fig. 9c) and grappa spirit (Fig. 9d), a similar behaviour of the polar charts to those obtained on solutions of equal composition of sugar or ethanol and temperature, is clearly observable.

If the content of the flask is sunflower oil, the power the system should deliver for tag activation is comparable to that required to obtain tag turn on and reply if positioned on the empty flask (Fig. 9e).

The salt content in the composition of the artichoke soup may have influenced the high needs in term of P_min in rear position. In this case, the data is very similar to that found for 1% and 2% sodium chloride solutions (Fig. 9f). For artichoke as well as for other soups, the presence of fibres, sugars and starch, which can be partly gelatinised and hydrolysed by cooking, may have different complex effects on dielectric properties also due to the percentage of free water reduction (Brinley et al., 2008).

4. Discussion

The results reported in this paper showed that the reading range of RFID tags is highly influenced by tag orientation with respect to the antenna, as well as by the chemical composition and temperature of the food product. Combinations of these factors, in some cases, drastically reduce the reading performance of UHF RFID systems. Different physical behaviours seem to condition the reading performances. Beside the tag-antenna mutual orientation, these can be mainly summarised as (1) reflection at the interface between two media having different dielectric constants, (2) EM field energy loss while penetrating into a dissipating medium, and (3) impedance detuning between the tag antenna and the receiver. The specific characteristics of the selected medium determine the weighted combination of effects (1-3) that can be observed from the data.

In the case of deionised water, the low readability performance can be attributed to different factors such as the reflection at the interface between two media having different dielectric constants (Jha et al., 2011) and the impedance mismatch and detuning (Bridelall and Hande, 2010) of the tag's RF circuit.

The temperature affects, as previously shown, the physical parameters of the food, leading to, as a consequence, variations on observed tag readability. In the case of sodium chloride solutions as well as of citric acid, the high power requested for tag activation can be ascribed mainly to losses in the liquid with an increasing imaginary part of permittivity (ε^''), which is typical of ionic compounds.

Organic compounds such as carbohydrates or alcohol can have an influence on the shape of the reading area at high concentrations. The very good performance of the tag in the vicinity of oil is probably due to the very low dielectric constant, which is reported to be 3.04 at 25 °C (Lizhi et al., 2008). This was also observed in fatty foods like milk cream. Indeed, ε' decreases when fat content increases as demonstrated for milk by Zhu et al. (2015).

5. Conclusions

By applying the method proposed in this paper, some of the aspects which affect the reading range of UHF tags for the identification of bottles containing food products in liquid form can be detected and considered to design optimised shelf positioning, labelling and reading systems.

It has been demonstrated that in many cases the reading range reduction can be overcome simply by changing tag orientation with respect to the reader antenna. The optimal orientation is highly influenced by food composition in terms of both quality and concentration. The choice of the reader antenna positioning and of the strategic points for identification (production line, storage room, transport, etc.) must also take into account the impact on readability of product temperatures.

The availability of food dielectric properties in the RFID standard UHF frequency band could be useful in predicting the reading range for RF identification of each product in the food industry. The results of this paper can be exploited to improve the reading performance of tags attached to food packed in plastic containers that are nowadays very commonly employed for food packaging. The effects of food items and packaging of different geometries should also be explored in order to design new products that are optimised also from the point of view of automatic identification.

Table 1. Declared nutrition facts on the label of the tested food products (g per 100 g) in compliance with Regulation 1169/2011 (European Commission, 2011).

	Skimmed milk	Milk cream	Sweetened tea	Grappa	Sunflower oil	Artichoke soup
Total carbohydrates	5.1	3.6	4.6	n.a.	0	5.4
Sugars	5.1	3.6	4.6	n.a.	0	1.8
Fibres	0	0	0	n.a.	0	1.2
Total fats	1.6	35	0	n.a.	92	1.0
Saturated fats	1.1	23.8	0	n.a.	18	0.2
Proteins	3.4	2.2	0	n.a.	0	1.3
Salt	0.13	0.1	0	n.a.	0	0.68
Ethanol	0	0	0	40	0	0

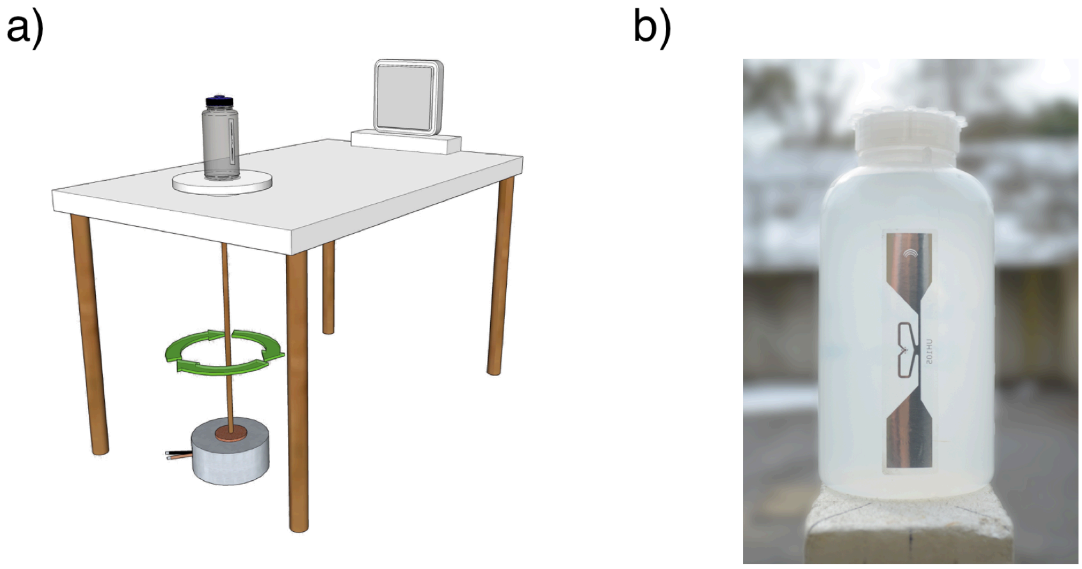

Fig. 1. a) Sketch of the test bench and b) picture of the UH 105 Lab-ID transponder attached on the empty flask.

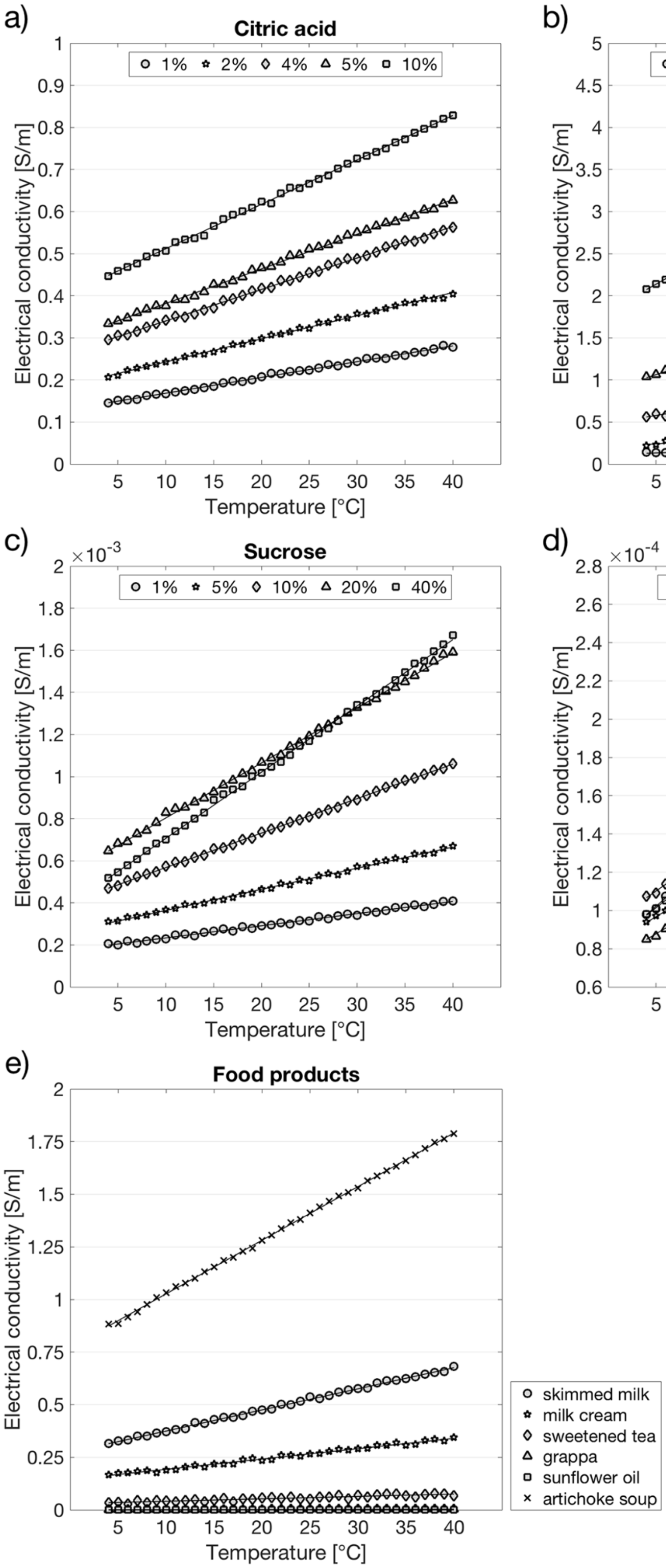

Fig. 2. Electrical conductivity (σ) [Sm-1] at different temperatures and concentrations of (a) citric acid, (b) sodium chloride, (c) sucrose, (d) ethanol solutions and (e) analysed food products.

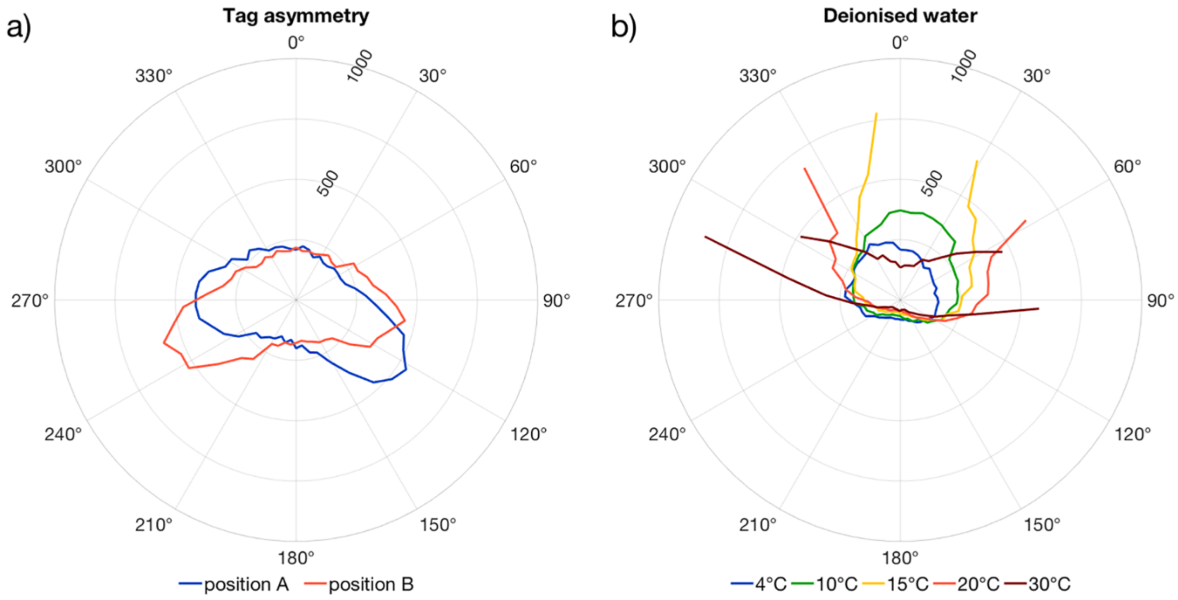

Fig. 3. a) P_min [mW] for activation of the tag when attached to an HDPE flask containing a solution of sodium chloride (0.2%) in position A and by reversing tag position by a 180° plane rotation around tag IC (position B). b) P_min [mW] for activation of the tag attached to a HDPE flask filled with deionised water at different temperatures.

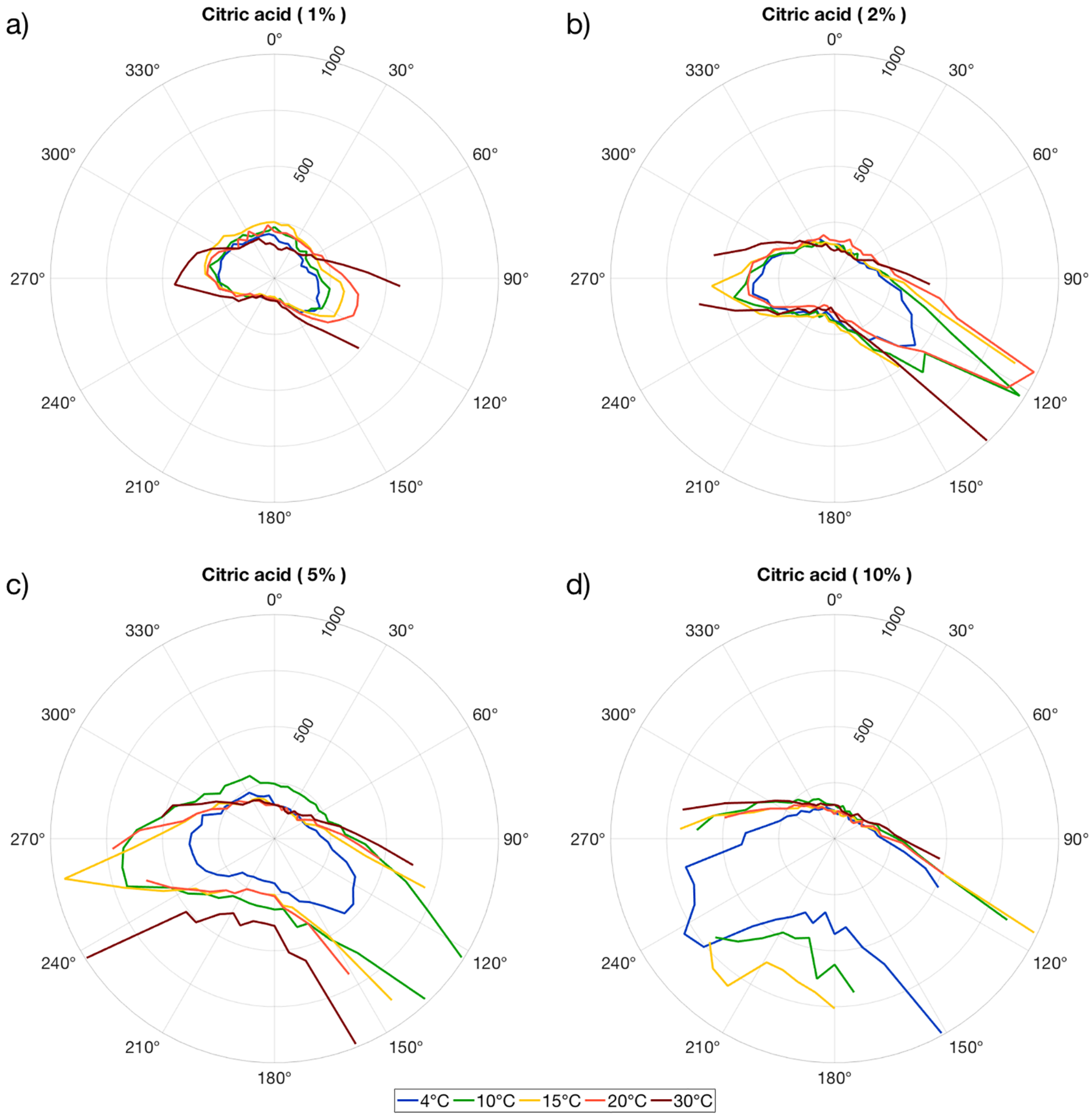

Fig. 4. P_min [mW] for activation of the tag attached to an HDPE flask containing citric acid solutions at different concentrations (1%, 2%, 5% and 10%) measured at different temperature (4, 10, 15, 20 and 30 °C).

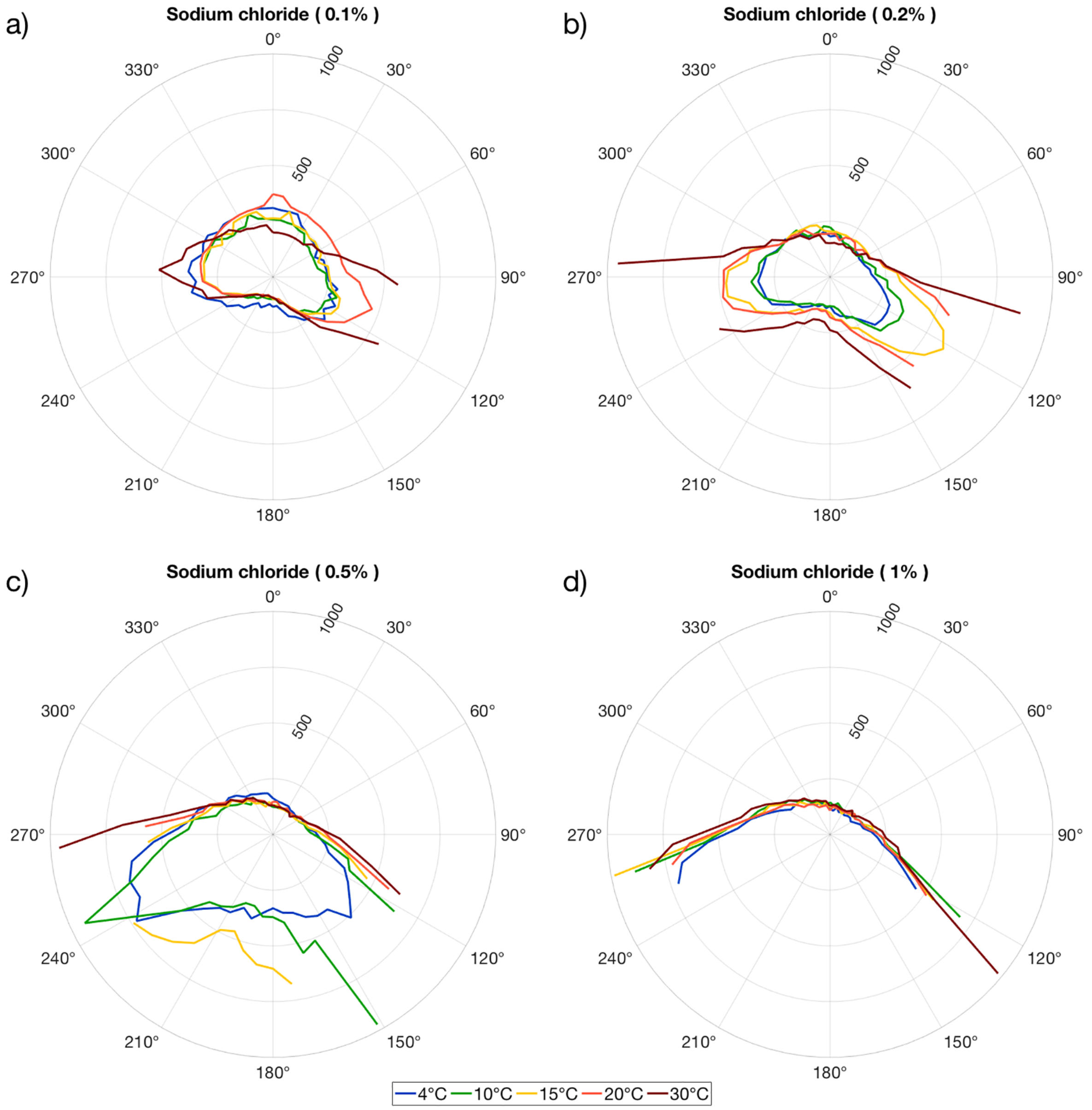

Fig. 5. P_min [mW] for activation of the tag attached to an HDPE flask containing sodium chloride solutions at different concentrations (0.1%, 0.2%, 0.5% and 1%) measured at different temperature (4, 10, 15, 20 and 30 °C).

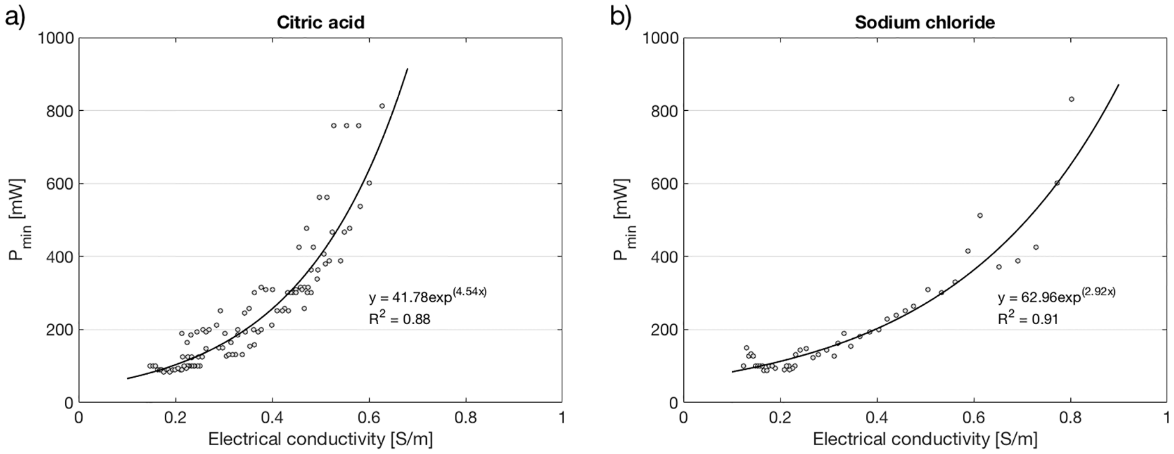

Fig. 6. Electrical conductivity effect on minimum power to activate the tag considering (a) citric acid and (b) sodium chloride solutions at all the tested concentrations. Tag at orientation angle of 180°.

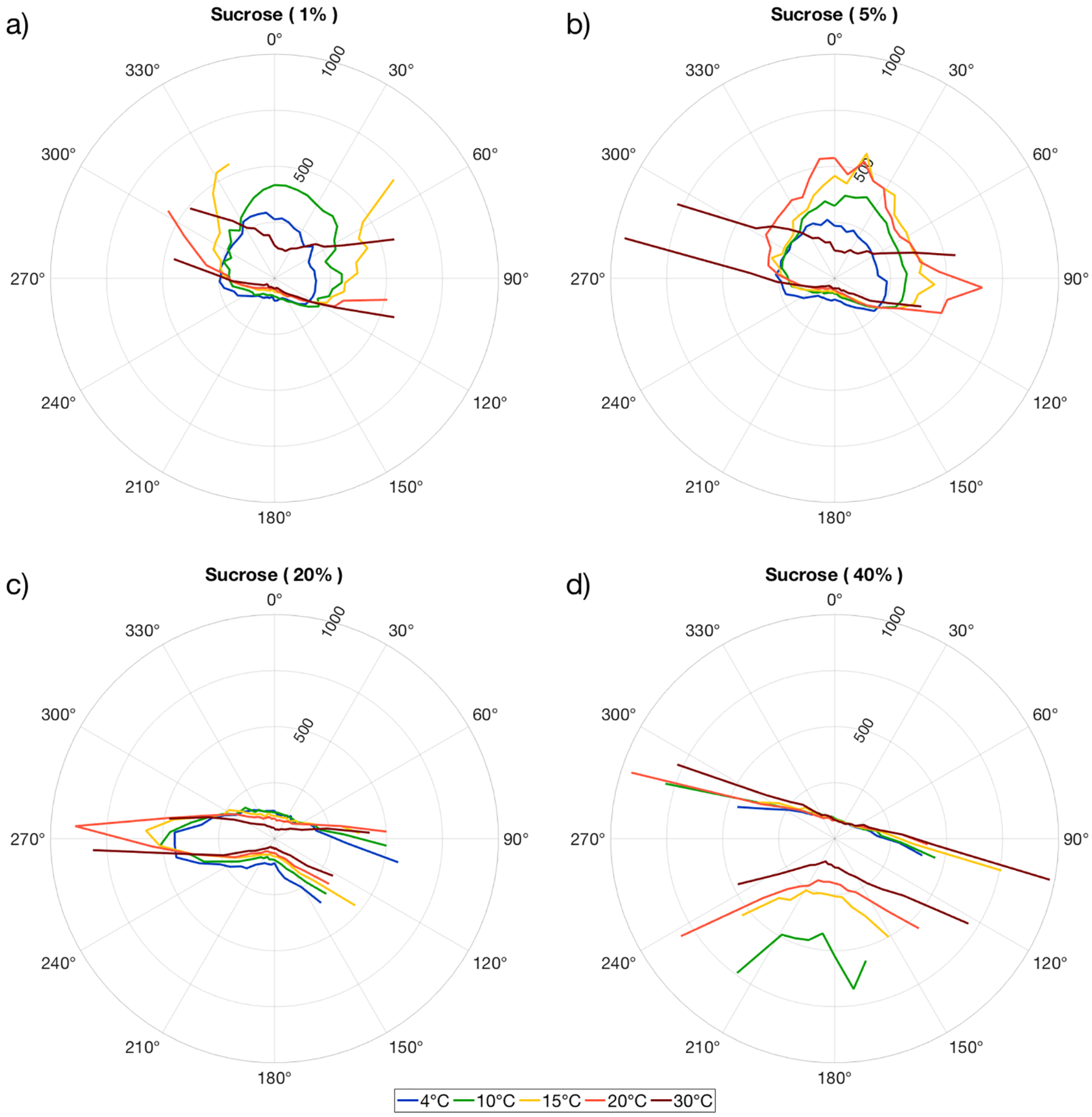

Fig. 7. P_min [mW] for activation of the tag attached to an HDPE flask containing sucrose solutions at different concentrations (1%, 5%, 20% and 40%) and temperatures (4, 10, 15, 20 and 30 °C).

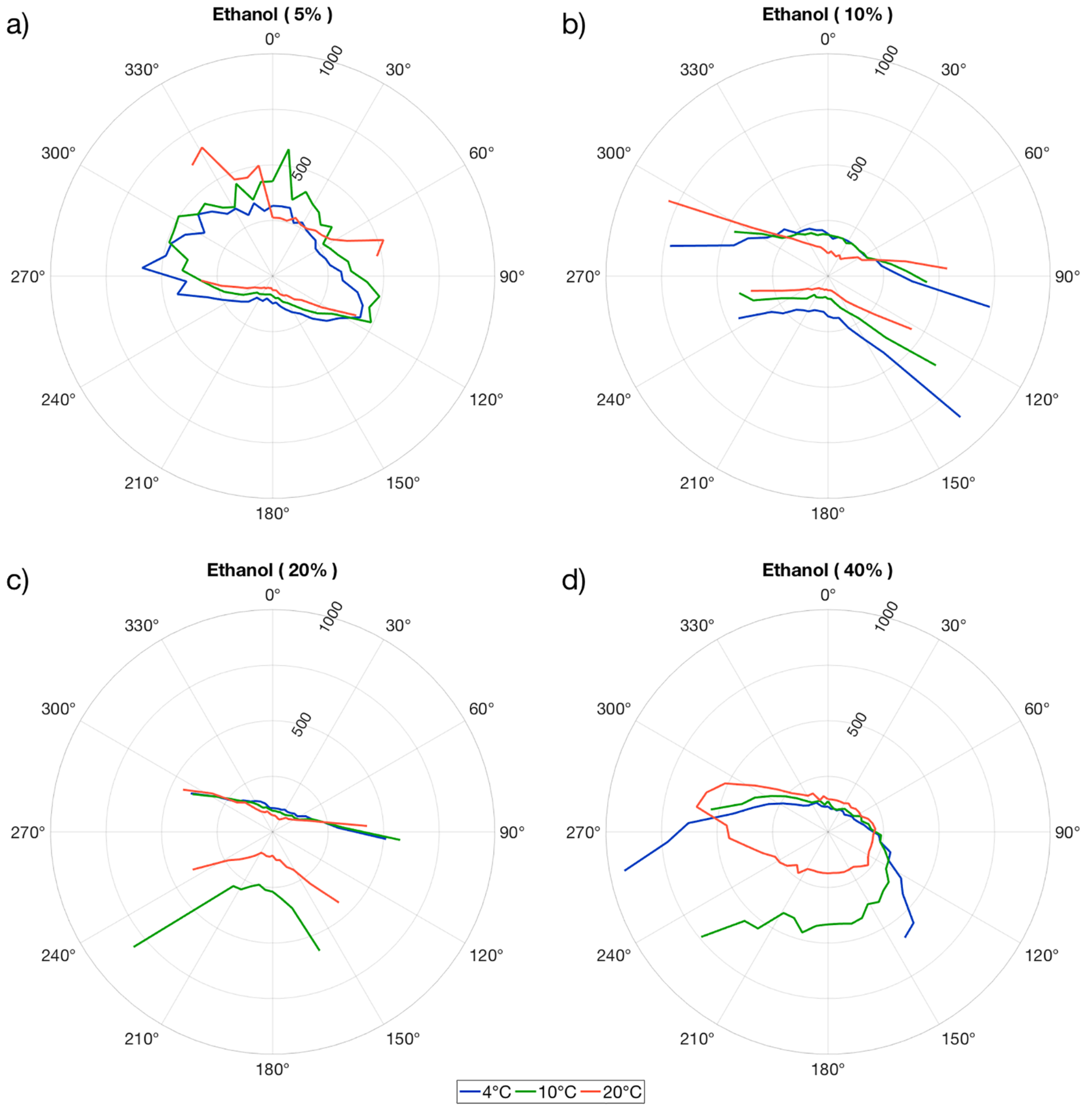

Fig. 8. P_min [mW] for activation of the tag attached to an HDPE flask containing ethanol solutions at different concentrations (5%, 10%, 20% and 40%) and temperatures (4, 10 and 20 °C).

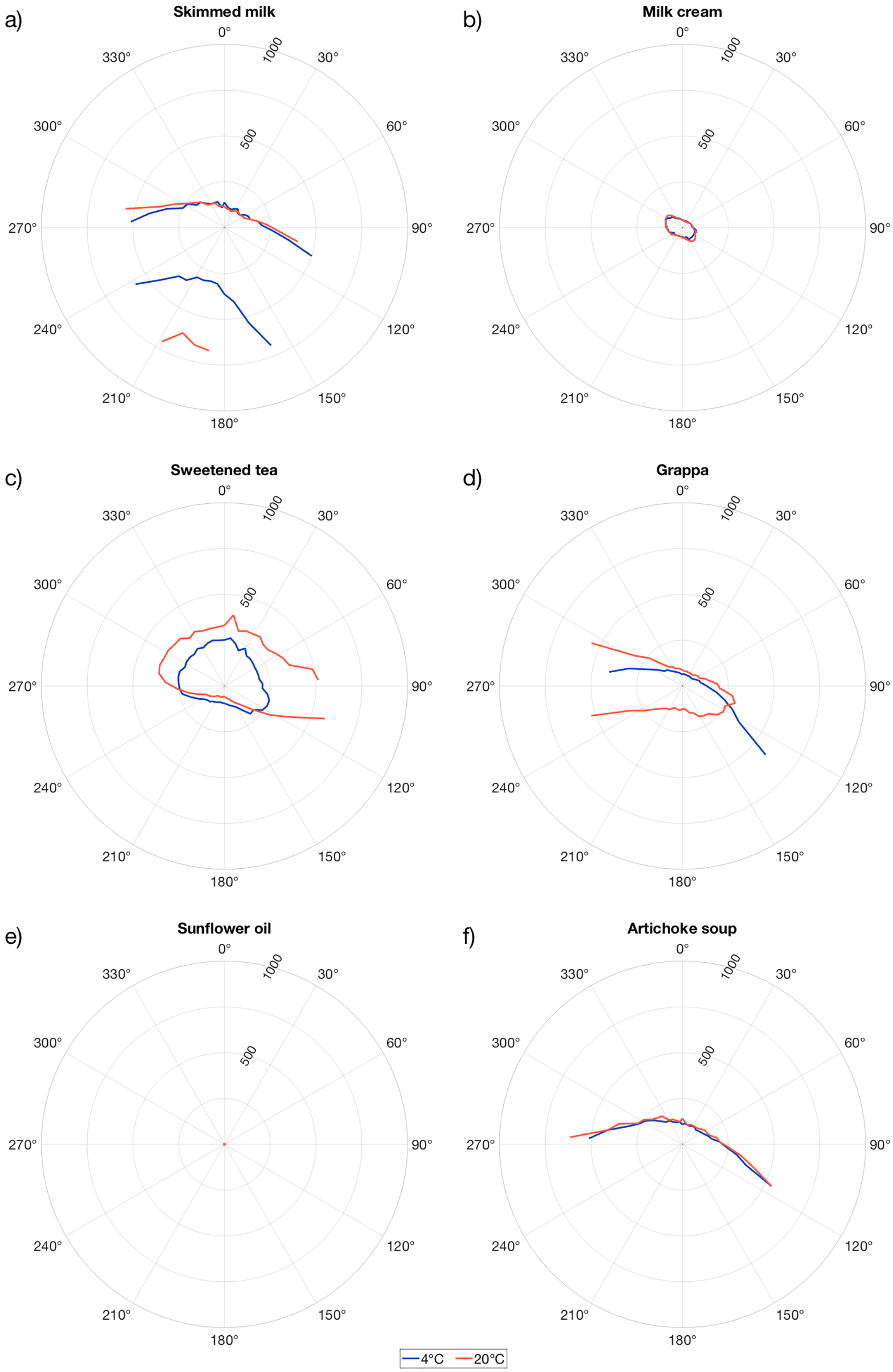
a)
Skimmed milk
b)
Milk cream
c)
Sweetened tea
d)
Grappa
e)
Sunflower oil
f)
Artichoke soup
0°
30°
60°
90°
120°
150°
180°
210°
240°
270°
300°
330°
500
1000
4°C
20°C

Fig. 9. P_min [mW] for activation of the tag attached to an HDPE flask containing retail food products (skimmed milk, milk cream, sweetened tea, grappa, sunflower oil, artichoke soup), measured at 4°C and 20°C.

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