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# Item-level Radio-Frequency Identification for the traceability of food products: application on a dairy product

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## Abstract

In the food industry, radio-frequency identification systems could be exploited for traceability, logistics as well as for anti-counterfeit purposes. In this paper, a complete item-level radio-frequency (RF) traceability system is presented for a high-value, pressed, long-ripened cheese. The main contribution of this paper consists in experimenting with different techniques for fixing tags to the cheese and solutions for automatic identification adapted to handling procedures as implemented in a dairy factory. All item movements are thus automatically recorded during the production, handling in the maturing room and warehouse, delivery, packing and selling phases.

Fixed and mobile RF devices operating at low, high and ultra-high frequency bands were considered for both static and dynamic identification of single/multiple cheese wheels. Factors such as tag type and shape, required power, antennas polarization and orientation, fixing method and ripening duration were considered in order to verify their effect on reading performance and system reliability.

**Keywords:** RFID, traceability, cheese

## 1. Introduction

Large food companies need supply chain management and logistics improvements to enhance their costs/benefits objectives (e.g. adopting pull marketing strategies, introducing lean strategies, reducing inventories and labour costs) and, at the same time, to guarantee the

34 highest level of traceability efficiency in terms of quality and safety. The application of  
35 innovative systems and technologies to collect information at item or batch level at  
36 affordable costs enables manufacturing enterprises both to better control the production  
37 process and to share quality and traceability data in supply chain collaborative networks  
38 (Bechini *et al.*, 2008; Barge *et al.*, 2009). The availability of a system which could  
39 continuously update inventories at supply chain level could lead to a reduction of costs tied  
40 to high inventory-to-sales ratios (Golan *et al.*, 2004; Varese *et al.*, 2008; Costa *et al.*, 2013).  
41 To our best knowledge, cheese traceability is currently managed at lot level and documented  
42 by written records. In the most favourable cases, the information is inserted in a local  
43 database. The application of innovative systems and technologies to automate information  
44 collection related to the single product unit could improve the performance of traceability  
45 systems (Dabbene and Gay, 2011) and optimize warehouse management and logistics  
46 (Alfaro and Ràbade, 2009), thereby reducing costs.  
47 Moreover, by means of traceability data sharing along the whole food supply chain, food  
48 safety would be increased and, in case of a recall, product withdrawal would be very rapid.  
49 In all cases, when data sharing is put in place, privacy issues should be attentively  
50 considered and managed (Lee and Park, 2010; Jacobs, 1996; Kumar and Budin, 2006).  
51 In the near future, due to the high risk of counterfeiting of labelled and certified products  
52 (e.g. the “made in Italy” products), new initiatives are expected to preserve the identity of  
53 valuable, high quality local products. Considering long-ripened protected designation of  
54 origin (PDO) cheese, the high value of the product is related to the preservation of credence  
55 attributes that cannot be perceived directly by the consumer, but can only be guaranteed by  
56 an effective, item-level, traceability system (Golan *et al.*, 2004). Identity preservation at item  
57 level is also important in case of special productions such as, for example, Kosher and Halal  
58 food or military supplies (Dabbene *et al.*, 2013).  
59 Single wheel identification by traditional methods (e.g. labels or brands), through the  
60 production process and during the maturing period, is critical due to cheese chemical  
61 composition (moisture, pH, fat and salt content), physical characteristics (texture, rind  
62 surface condition), environmental conditions during the different processing phases (curd  
63 moulding, pressing, dry or brine salting, ripening), and frequent product handling (e.g. daily  
64 turning, brushing and scraping during ripening).

65 Radio-frequency identification (RFID) systems have already been adopted for traceability  
66 purposes in many food supply chains (Nambiar, 2010), combining optimization (Sarac *et al.*,  
67 2010; Tajima, 2007) with real-time monitoring (Abad *et al.*, 2009; Wang *et al.*, 2010). In  
68 spite of today's wide diffusion of RFID in animal identification (by ear tag or endorumenal  
69 bolus, e.g. Eradus and Jansen, 1999; Gay *et al.*, 2008; Jansen and Eradus, 1999; Barge *et al.*,  
70 2013 and references therein) and in livestock feeding and milking management (Trevarthen  
71 and Michael, 2008), RFID adoption in the cheese industry is rarely deployed and is often  
72 limited to packed products kept in boxes and/or stacked on pallets (Wamba and Wicks,  
73 2010).

74 When properly coated by special resins or plastic materials approved for food contact, RFID  
75 transponders could be directly inserted in long-ripened cheese, allowing the assignment of a  
76 unique numerical identifier, stored in the tag, for each wheel of cheese. This application,  
77 however, is faced with various problems, among which the persistence and readability of the  
78 tag from pressing to ripening and delivery. In addition, the high moisture content of the  
79 cheese could strongly attenuate the RF signal, thereby limiting, or even compromising,  
80 reading performances.

81 Preliminary studies have been conducted by applying tags to Spanish PDO cheese (Pérez-  
82 Aloe *et al.*, 2007; Pérez-Aloe *et al.*, 2010), and to the high-value Italian cheese *Parmigiano*  
83 *Reggiano* (Regattieri *et al.*, 2007). In 2007, through a European project conducted by the  
84 Department of Logistics at the University of Dortmund, a traceability system based on  
85 RFID technology was developed for *Queso Cabrales* (a famous PDO Spanish cheese).  
86 Nevertheless, to our best knowledge, a complete study on the reliability of an RFID tracking  
87 system for cheese identification in an industrial context is not yet available. Some aspects,  
88 like the persistence of the different types of tags on the cheese and the reading performances  
89 at different frequencies, should be determined and considered when integrating the system in  
90 the traceability management of a dairy factory.

91 The aim of this paper is to investigate the effectiveness of RFID technology in tracing single  
92 cheese wheels, from curd making to final packaging and delivery. RFID systems, operating  
93 at low, high and ultra high frequencies (LF, HF and UHF respectively), were tested and  
94 compared with the aim of evaluating the performances and limits of each solution at  
95 different stages of the production process. Performance evaluation of RFID systems requires  
96 RF measurements that have to be conducted in strictly controlled conditions (Derbek *et al.*,

97 2007). The dielectric properties and shape of food matrices usually affect tag reading ranges  
98 (i.e. the longest tag-to-reader antenna distance that still guarantees tag activation, data  
99 processing and answer transmission), reading zones (i.e. the region where the tag is detected)  
100 and the transmitted power required for tag activation. The reliability of RF identification  
101 needs to be evaluated for each category of food product, in the production and logistics  
102 phases as well as in the different environments.

103 The assessment of the coverage zones and of the transmitted power required for transponder  
104 activation in the laboratory as well as in the cheese factory will be used to identify the  
105 potentialities of different RFID solutions in each cheese production phase. The issue of the  
106 proper design of the facilities required for cheese wheel identification as well as the  
107 positioning of the reader antennas will be discussed on the basis of experimentation results  
108 which have been obtained in a local dairy factory, and regard *Toma Piemontese*, a typical  
109 PDO cheese that can be considered representative of most medium and long-ripened cheeses  
110 in Piedmont.

111 The paper is structured as follows: in Section 2 the joined production process and  
112 information flow are analysed in order to define strategic points in the dairy factory where  
113 products have to be identified to guarantee continuity through traceability. Section 3 reports  
114 the materials and the protocols used in the experimentation. The results of the  
115 experimentation are discussed in Section 4. The proposal for an RFID system for item-level  
116 traceability in a cheese factory is described in Section 5. Finally, conclusions are drawn in  
117 Section 6. Supplementary materials, consisting of a set of additional figures, hereafter  
118 indicated as S1 to S7, are available online alongside the electronic version of the paper.

119

## 120 **2. Products & information flow in a dairy factory**

121

122 To determine the points and phases where/when the product has to be identified, a dairy  
123 factory (Valle Josina, NW of Italy), was considered as a sample. The factory transforms  
124 about 50 tons of milk daily to produce four kinds of long-ripened cheese (*Bra Tenero*, *Bra*  
125 *Duro*, *Raschera* and *Toma Piemontese*). The PDO cheese considered in this paper (*Toma*  
126 *Piemontese*) is a long-ripened, pressed, semi-fat, semi-hard texture cheese obtained from  
127 whole cow milk, raw or pasteurized (D.P.C.M., 1993). Following the standards for *Toma*  
128 *Piemontese* cheese, the wheels are moulded in cylindrical moulds of 30 cm in diameter and

129 8-9 cm in height. Ripening lasts 60 days. The dairy factory currently adopts an internal  
130 cheese traceability system at lot-level. Fig. 1, in the middle column, reports the flow chart of  
131 the cheese production process while, on the left of Fig. 1, the related information flow of the  
132 already existing traceability system is described. On the right of Fig. 1, the proposed RFID-  
133 based traceability system is depicted and is further discussed in Section 5.

134 The traceability of milk presents the same criticalities as other liquid or bulk products, which  
135 are usually stored in tanks and progressively merged during the production process. As  
136 discussed in Comba *et al.* (2013), traceability during the processing of these kinds of  
137 materials can be guaranteed by combining the information of the supplied lots, according to  
138 the mixing rules. This methodology generates, whenever necessary, new traceability units  
139 (TU) of homogeneous products (see Moe, 1998, for a formal definition of TU).

140 For milk, TUs generated during the collecting phase are typically rather small, allowing  
141 incentive premiums on the milk price on the basis of quality parameters (e.g. pH, presence of  
142 antibiotic residues, protein and fat content, somatic cells number and total microbial count).

143 In the considered dairy factory, a new TU – the dairy milk lot – resulting from the blending  
144 of several farm milk lots, is then defined. Here, the traceability system links information  
145 about input milk and dairy lots. From each dairy lot a batch of about 110 cheese wheels is  
146 obtained by pasteurization and curdling. Traceability information is manually noted on a  
147 form and on a paper ticket which report the milk lot, the cheese lot number and curdling  
148 parameters as well as the milk enzymes and the rennet type, the process temperatures, the pH  
149 level, the curd pieces dimensions and the type of salting. When the whey removal process is  
150 finished, the whole fresh broken curd is cut in rectangular chunks which are then placed into  
151 a circular stainless steel mould where they will be pressed for 24 hours. From this point, in  
152 the dairy traceability system, cheese lot identification is guaranteed by the cheese batch  
153 traceability ticket which reports the product type, the production date, the lot number, the  
154 number of cheese wheels in the lot, the milk lot tank number and the date of the expected  
155 end of maturing period. This ticket follows the cheese lot through all production stages.

156 After the pressing phase, the cheese wheels are moved to the salting zone (Fig. S2, on the  
157 left) where cheese salting can be done according to two procedures: dry or brine salting. In  
158 brining, the cheese wheels are immersed in a saturated brine solution for 24 h while dry  
159 salting is carried out by pouring salt on each cheese side with wheels arranged on shelves for  
160 48 h (24 hours for each cheese face).

161 In this phase, traceability is highly critical as the lot identification paper card isn't applied to  
162 the product but is kept near the brine tank, leading to potential errors. After 24 hours of  
163 brining or 48 hours of dry salting, cheese wheels are ripened at 8–10 °C for up to 60 days. In  
164 the ripening rooms, traceability is kept by the paper ticket placed nearby the first wheel of  
165 the lot, while the following are identified only by their position according to an established  
166 pattern.

167 At the end of the maturing period, each wheel of the batch is brushed, packed and stored into  
168 a loading area. The identifier of the whole lot is the paper ticket. In case the lot is  
169 disassembled, traceability of each item is guaranteed by maintaining the individual lot  
170 physically separated in the loading area, where the sold items are progressively picked.  
171 Before shipping, each cheese wheel is scanned by a metal detector and labelled. A delivery  
172 note detailing the quantity and the type of products must be filled.

173

### 174 **3. Materials and methods**

175

#### 176 **3.1 Radio-frequency identification systems**

177 As the readability of passive tags attached on food items is strongly influenced by the  
178 wavelength of the RF signals, systems at different frequencies (LF, HF and UHF) were  
179 tested and compared in order to determine solutions that could be effectively applied to  
180 cheese tracking during the manufacturing, warehousing, packaging and distribution phases.

181 Different types of passive transponders were selected (Table 1), apart from the operating  
182 frequency, on the basis of their ruggedness in the harsh environment and their compatibility  
183 with food contact. Some tag models (*a*, *b*, and *c*) were coated by materials suitable for food  
184 contact and resistant to mechanical shocks, while in the rest, normally used for other  
185 purposes (e.g. logistics), the inlay was only covered by a plastic film. Some tag antennas (*e*,  
186 *g*, and *h*) were prototypes employed in previous experimental works (not cited).

187 Two different handheld devices were tested for static tag reading in cheese factory trials: a  
188 PDA Psion Teklogix – Workabout PRO equipped with an LF or HF frequency range  
189 module, and an Idc Ant 200/200 I-Scan mobile antenna, composed of a reader worn at the  
190 waist of the operator and coupled to a square loop HF antenna (200 x 200 mm). Both devices  
191 were tested for the identification of cheese wheels positioned on shelves. LF tests were



192 performed using a BlueBox Soltec reader (version FW 1.11) linked to a Bluebox 125 kHz  
193 panel antenna (200 x 200 x 15 mm).

194 Two different fixed HF systems were tested: a commercial long-range system (Obid, 15693  
195 and 18000-3 ISO standards compliant, with a panel antenna of 600 x 800 mm) and a self-  
196 constructed prototype antenna with a circular loop customized on the basis of the cheese  
197 wheel shape. The transmitter power output (TPO) was set to 2 W.

198 Fixed panel antennas were adapted to cheese wheels electronic identification in static  
199 conditions during specific operations (e.g. transport, handling and/or packaging). The  
200 circular HF antenna prototype was composed of a single loop of 138 cm of length (equal to  
201  $\lambda/16$ ) built with an RG58 coaxial cable and connected to a dynamic antenna tuner (DAT) for  
202 impedance matching with the HF reader (see Fig. S4, on the left).

203 Reading tests were then performed for *Toma* DOP cheese tracking at strategic points of the  
204 production process. For this purpose, 18 *Toma* wheels were equipped and then electronically  
205 identified by using twelve different passive transponder models (Tables 1, *a, b, c, e, f, g, h, i,*  
206 *l, x, v, z*) positioned on the side of the cheese wheel or on the edge of the cheese curved  
207 surface. Tags were applied during curd moulding (Fig. S1, on the right) and were covered  
208 with or layered between one/two casein disks (Fig. S1, on the left) before the two pressing  
209 phases expected for *Toma* production (Fig. S2). Half of the wheels were left in brine for 24  
210 hours, while the remaining were dry salted for 48 hours (24 hours for each side). Finally, the  
211 cheese was ripened for 60 days in refrigerated cells. Tag readability was checked after  
212 salting and then periodically during cheese ripening by means of a palmtop handheld device.  
213 Tag-to-PDA reading distances were recorded at the end of ripening.

214 As UHF RFID-systems performances are affected by water and metals, the proposed  
215 systems were preliminarily studied in controlled conditions inside an RF semi-anechoic  
216 chamber to eliminate any possible environmental interference and/or signal reflection. To  
217 compare readability of the tag at different orientations, both linear and circular antennas  
218 were considered and several tag and antenna combinations were tested to identify the most  
219 favourable solution for item level identification. Then, the RFID interrogation in the UHF  
220 band was carried out by using a Caen RFID R4300P standalone reader connected to  
221 antennas generating circular polarized (Caen RFID, model Wantenna X005, 7 dBi gain) or  
222 linear polarized (Caen RFID, model Wantenna X007, 8 dBi gain) fields. The reader was  
223 controlled by a C# software specifically developed by using the CAEN Application

224 Programming Interface. This application allowed measuring of the minimum tag activation  
225 power ( $P_{min}$ ), defined as the minimum TPO required to activate and read the unique code  
226 contained in the tag (Rao *et al.*, 2005). This was obtained by means of a power sweep  
227 ranging from 0 to 2000 mW with 1 mW steps (Tortia *et al.*, 2012).

228 All the UHF devices used in the trial were EPC Class 1 Gen 2 protocol compliant.

229

### 230 **3.2. Interrogation area and maximum reading distance assessment methods**

231 Laboratory tests were set up to determine the interrogation zone with different tag/antenna  
232 combinations in the LF and HF bands, firstly with tags applied on a polystyrene support and  
233 then with tags applied to the cheese wheel surface. Tag orientation was always parallel to the  
234 reader antenna. Cross-sections of the reading volume were determined by using the  
235 transponders described in Table 1, with the purpose of evaluating solutions for static cheese  
236 identification like, for example, integrating the antenna in a cutting board or under the  
237 conveyor belt immediately after the metal detector before shipping (see Fig. S7). In the case  
238 of cheese wheel identification, tags were attached on the cheese rind at the centre of one face  
239 or on the outer edge. Moreover, tags were applied both on the cheese surface oriented  
240 towards the antenna and on the opposite side to evaluate the effect of cheese mass on the  
241 reading distance. Rectangular shaped tags were applied by orienting the longer edge along  
242 the  $y$  axis.

243 The shape of the reading zone was obtained by approaching the transponder towards the  
244 antenna till detection. To describe the shape in three dimensions, measurements are referred  
245 to the  $x$ ,  $y$  and  $z$  axes with the origin at the antenna geometric centre, with the  $x$  and the  $y$   
246 axes aligned along the shorter and longer sides of the antenna respectively, and the  $z$  axis  
247 orthogonal to the antenna plane.

248 The maximum reading distance ( $D_{max}$ ) between tag and antenna was measured along the  $z$   
249 axis at fixed  $x$ ,  $y$  points on the antenna plane as proposed also by Porter and Billo (2004).  
250 Different  $xz$  cross-sections at increasing  $y$  values were also determined. When the tag was  
251 applied on the cheese outer edge, the cheese wheel face laid on the  $xz$  plane with the tag in  
252 parallel orientation to the antenna, as in the aforementioned cases.

253 The maximum reading distance  $D_{max}$  at  $x = y = 0$  was also determined with the tag on  
254 polystyrene and on the cheese surface to evaluate the influence of the tag type and the  
255 feasibility of tag detection across the cheese. Towards this aim,  $D_{max}$  was also recorded after

256 a 180 degrees rotation of the cheese wheel around the  $y$  axis. In this case the cheese remains  
257 interposed between the antenna and the tag.

258 A plastic cutting board with an embedded HF RFID antenna was designed and implemented.  
259 The reading volume of such a prototype of smart cutting board was determined in static  
260 conditions by using the  $c$  tag model. The tag was applied both on the cheese surface and on  
261 the outer edge respectively in parallel and perpendicular orientations to the antenna plane.  
262 The performances of the system in dynamic conditions were evaluated by measuring the tag  
263 detection rates  $Dr\%$ , defined as the ratio between the number of successful identifications  
264 and the total number of tests (100 repetitions per trial) which were performed manually by  
265 placing the cheese wheel on the prototype of the HF cutting board in random position (Fig.  
266 S4, on the right). The cheese was arranged on the antenna plane by ensuring the tag was  
267 inside the cutting board perimeter and then moved outside the antenna reading volume  
268 before the next repetition. The tests were performed using six RFID tag models ( $c$ ,  $e$ ,  $f$ ,  $g$ ,  $i$ ,  
269  $l$ ).

270

### 271 **3.3 Characterization of UHF systems for cheese electronic identification in anechoic** 272 **chamber**

273 The minimum power  $P_{min}$  that has to be delivered to the reader output to activate the tag and  
274 receive the backward signal is described by the *Friss* transmission equation concerning RF  
275 propagation between transmitting and receiving antennas. The power received by the tag  
276 chip is a function of the distance separating the transmitting (reader) and receiving (tag)  
277 antennas and of their respective gains (Rao *et al.*, 2005; Nikitin *et al.*, 2007). Factors that can  
278 negatively affect reading distance are: tag chip-to-antenna impedance mismatching, tag  
279 orientation, frequency detuning and hardware parts which determine losses.

280 As the reading range is not only dependent on the tag itself, but also on the tag support  
281 material and on the shape of the antenna (e.g. meander-line, bow-tie, cross-dipole, U-shaped  
282 slot antenna) which can react differently in contact with the cheese or other materials,  
283 different tag antenna shapes were tested. The UHF reader was connected, in different  
284 experiments, to the linear and circular polarized antennas at increasing tag-to-antenna  
285 distances. The reading antenna and the tag centres were always aligned. To reduce the effect  
286 of the environment and of possible external disturbances to a minimum, experiments were  
287 conducted inside a semi-anechoic chamber (Fig. S5).

288 The developed software was used to determine  $P_{min}$  at different tag-to-antenna distances.  
289 For each tag model,  $P_{min}$  was preliminarily measured with transponders applied on a  
290 polystyrene support. Then, to evaluate the effects of the presence of *Toma*,  $P_{min}$  was recorded  
291 with tags directly applied to the cheese wheels surface. Tests were carried out by using four  
292 cheese wheels belonging to two production lots: two ready for sale (60 days of ripening) and  
293 two ripened for 30 days. As the reading range was limited by the cheese, the tag-to-antenna  
294 distance was set at 0.5 m. Experiments were repeated using a 3 mm thick plastic spacer  
295 between tag and cheese, to evaluate possible reduction of the cheese absorbing effect on the  
296 RF signal.  
297 In the experiment design, results in terms of  $P_{min}$  for all the combinations of antenna  
298 polarization (linear or circular), ripening duration (30 or 60 days), tag type (five tags), and  
299 presence/absence of a spacer between tag and cheese factors were collected and statistically  
300 analysed using SPSS<sup>®</sup> Statistics 17.0. The separate effects of the considered factors and their  
301 interactions were evaluated by one-way analysis of variance procedure (UNIANOVA) for  
302 regression and variance analysis of the dependent variable. A generalized linear model  
303 (GLM) was adopted. Means were then compared by a post-hoc Tukey test.

304

## 305 **4. Results**

306

### 307 **4.1 Transponder persistence**

308 All the housings in different covering materials (Table 1) were apt to protect the tags  
309 circuitry and antennas. In fact, in spite of the harsh environment and the cheese handling and  
310 brushing, tag resistance to mechanical shock and to critical chemical and storage conditions  
311 was enough to guarantee the correct reading of the transponders during the whole production  
312 process.

313

### 314 **4.2 Detection zone of fixed and handheld LF and HF systems for cheese wheels** 315 **identification**

316 The reading zone of the 125 kHz LF panel antenna is represented by its  $xz$  cross-sections  
317 (Fig. 2). The maximum reading distance  $D_{max}$  of tag  $b$  exceeded that of the smaller tag  $a$  by  
318 about 60 mm in the case of tags applied on polystyrene. The presence of the cheese only had

319 a slight effect on the reading distance, as can be seen for the  $y=0$  cross-section for tag *a*  
320 attached on the two different materials.

321 For tag *a* applied on the cheese, cross sectional areas at different  $y$  values are reported. The  
322 main reading lobe shape resulted symmetric with respect to the  $z$  axis. When the tag was  
323 reaching the border of the antenna, it was detected only when it was very close.

324 When a tag was placed between the antenna and the cheese wheel, the reading zone was a  
325 circle of 100 mm radius. On the contrary, when the tag was placed on the opposite side of  
326 the cheese wheel, whose thickness ranges between 90 and 100 mm, correct reading was  
327 achieved inside a circle of only 60 mm radius around the  $z$  axis.

328 The shape of the reading zone for tag *b* was similar to the one obtained for tag *a*, but slightly  
329 larger (data not reported). Tag *a* was correctly identified by the PDA handheld device only  
330 with the RFID module in contact with the cheese surface, while tag *b* was detected at a  
331 maximum distance of 70 mm (results reported in Table 2).

332 As determined in laboratory conditions, the shape and dimensions of the reading zone of the  
333 rectangular Obid *i*-scan HF antenna differ depending on tag model, tag-to-antenna mutual  
334 orientation and cheese wheel presence. The maximum reading distance  $D_{max}$  measured along  
335 the  $z$  axis at  $x = y = 0$  is reported, for each tag model, in Table 3.

336 On polystyrene, a direct proportionality relationship between tag dimension and tag-to-  
337 antenna maximum reading distance could be clearly evinced. The maximum reading  
338 distance of the smaller tag *c* resulted approximately equal to one third of the bigger one (tag  
339 *l*). For rectangular tags, the maximum reading distance  $D_{max}$  resulted proportional to the  
340 length of the longer edge of the tag, rather than to other tag parameters (e.g. tag area).

341 To compare the influence of cheese presence on the tag-reading zone, the information is  
342 expressed as the ratio between  $D_{max}$  obtained when the tag was applied to the cheese surface  
343 and  $D_{max}$  obtained on the polystyrene (%). Except for tag *c*, whose maximum reading  
344 distance was not reduced at all by cheese presence, the maximum reading distance of all the  
345 tags applied to the *Toma* cheese wheel was reduced to some extent. When the tag was lying  
346 on the cheese face, the presence of the cheese affected  $D_{max}$  to a lesser extent than in the case  
347 of a tag applied on the outer edge.

348 When the tag was attached on the cheese face, the effect of a 180 degrees rotation around the  
349  $y$  axis was null except for tags *d* and *f* which were the smallest among the rectangularly

350 shaped ones. In that case, the presence of the cheese wheel thickness among receiving and  
351 transmitting antennas didn't affect tag antenna communication efficiency.

352 On the contrary, apart from tag *c*, tag application on the cheese outer edge significantly  
353 decreased the maximum reading distance for all the considered tags and the 180 degrees  
354 rotation further reduced  $D_{max}$  only for tags *d* and *m* (a square model).

355 Tag *d*, applied on the cheese outer edge with a 180 degrees rotation on the *y* axis, was not  
356 even readable.

357 The *xz* cross-sections of the reading zone for tag *l* on the cheese surface ( $y=0$ ) and on the  
358 polystyrene at different *y* values can be observed in Fig. 3. For all the considered HF tag  
359 models, without cheese, the reading cross-section area shape in parallel orientation at  $y=0$   
360 was constituted by three lobes. When the tag was applied on the cheese surface, both size  
361 and shape of the antenna reading volume cross-section ( $y=0$ ) were significantly reduced. In  
362 particular, the side lobes resulted smaller, except for tag *l* (Fig. 3, dotted line). The reading  
363 zone shape obtained in the presence of cheese was similar to that measured without cheese.

364 The shape of the reading area of the prototype HF cutting board (Fig. 4) is similar to a  
365 spheroid with an equatorial radius  $R_a$  equal to 290 mm, and a distance from centre to pole  
366 along the symmetry axis ( $L_b$ ) of 195 mm if tag orientation is parallel. The embedded circular  
367 loop antenna can then read the tag applied on both cheese faces placed on the whole cutting  
368 board surface, with the exception of a non-reading area that corresponds to the tag alignment  
369 with the antenna loop cable. This is due to the orientation of the electromagnetic field lines  
370 of force typical of inductive coupling. When the tag was applied on the cheese outer edge, in  
371 perpendicular orientation with respect to the antenna horizontal plane, the resulting reading  
372 area was smaller and shaped like a torus having a minor radius  $R_c$  equal to 127 mm and a  
373 major radius  $R_d$  equal to 216 mm. The radius  $R_c$  (Fig. 4) represents the distance between the  
374 cutting board centre and the external limit of the torus reading area (i.e.  $R_c = R_d - R_e = 89$  mm)  
375 and represents the radius of the central no-reading zone. Consequently, tag reading is  
376 possible only if the cheese wheel is well centred on the cutting board, when the tag remains  
377 within the torus reading volume.

378 By handheld device, the reading distance of HF tags ranged between 50 and 130 mm as  
379 shown in Table 2. When a handheld device was connected to a single loop portable antenna,  
380 the reading distance ranged between 150 and 200 mm.

381

### 382 **4.3 Detection rate of cheese wheels on an HF cutting board**

383 Table 4 reports the results of dynamic repetitive positioning of the cheese wheel, at 2 W  
384 TPO, for the considered tag models. Detection rate  $Dr\%$  was always the highest when tags  
385 were in parallel orientation and indifferently positioned on the upper or lower cheese face for  
386 all the considered tags. In the case of a tag placed on the cheese edge, perpendicularly  
387 oriented with respect to the antenna plane,  $Dr\%$  decreased for tag models  $c$ ,  $g$  and  $f$ , while it  
388 was null for tag type  $e$ . Conversely, tag  $i$   $Dr\%$  reduction was null when applied on the cheese  
389 wheel outer edge.

390

### 391 **4.4 Effects of the cheese on tag readability in ultra high frequency identification**

392 For each combination of reader antenna, tag type and support (polystyrene or cheese), an  
393 appropriate reading distance was chosen in order to obtain a measured power value in the  
394 required range. As the energy required to activate the integrated circuit is almost equal for  
395 any tag type, the effects on  $P_{min}$  could be ascribable to the contact with high dielectric  
396 materials such as products with high water content, which cause an alteration of the  
397 electrical characteristics of the tag antenna causing an impedance mismatch. Besides,  
398 emitted power is dissipated inside the cheese and part of the wave is reflected (Lorenzo *et*  
399 *al.*, 2011). Since the system is not linear (tag detection acts as a threshold), the lower  $P_{min}$  is  
400 required, the less these effects occur.

401 Moreover, as the tag antenna shapes are different, tag response in linear or circular  
402 polarization fields vary. On polystyrene, at 1.5 and 2.0 m distance between linear polarized  
403 antenna and tag, all tag types were detected at very low transmitted power. Measured  $P_{min}$   
404 values resulted even lower than the lower threshold of the reader operating range ( $\approx 43$   
405 mW), except for tag  $o$  which resulted not readable (out of range,  $P_{min} > 700$  mW) at 2.5 m.  
406 For tags  $n$ ,  $p$ ,  $q$ , and  $r$ , the optimal reading distance was 2.5 m (Fig. 5).

407 Since the  $P_{min}$  values obtained at 2.0 m with the circular polarized antenna are higher and  
408 since the differences in  $P_{min}$  among the tags are more easily underlined, the optimal tag-to-  
409 reader antenna distance with the circular polarized antenna resulted equal to 2.0 m. At a 2.5  
410 m distance, the minimum required power was high and the reading was very difficult for all  
411 the tags and only tags  $n$  and  $p$  (both dipoles) were detectable by the circular polarized  
412 antenna.

413 As a result, different tag designs and antenna polarizations led to different required  $P_{min}$  for  
414 tag activation and correct signal backscattering. For all the considered transponders,  $P_{min}$  was  
415 significantly higher with a circular polarized antenna whose gain is lower with respect to the  
416 linear polarized antenna.

417 On polystyrene, tag *o*, which is a cross-dipole, was found to be activated only at higher  
418 emitted power with both antennas. When the transponders were attached to the cheese  
419 wheel, the power required to activate the tag and to have a response increased and, as a  
420 consequence, the tag-to-reader antenna distances considered in the trials were reduced to 0.5  
421 m.

422 Reading by handheld device at the beginning of ripening was not possible, while after two  
423 months all tags were identified even if, in some cases (tag *v*), the antenna module of the  
424 handheld device had to be in contact with the cheese (Table 2).

425

#### 426 **4.5 Statistical analysis**

427 Table 5 reports the mean values of  $P_{min}$  required for tag activation on the cheese, calculated  
428 by considering 156 readings and including the effects of all the factors, such as antenna  
429 polarization, ripening period and spacer presence/absence. The lowest value of  $P_{min}$  when the  
430 tag was applied on the cheese was registered for tag model *n*. In particular, cheese presence  
431 affected readings for tags *q* and *p*, even if, on polystyrene, good results were achieved. On  
432 the contrary, for tags *o* and *r* cheese presence ameliorated tag performances with respect to  
433 polystyrene. The effect of the factors and the interactions between the factors on the variable  
434  $P_{min}$  as evinced from UNIANOVA are reported in Table 6.

435 The effects of the ripening duration factor were not significant for  $P < 0.05$ . This could  
436 probably be due to the fact that the first layers of the cheese rind lost moisture especially in  
437 the first days (Goy *et al.*, 2012), however rind characteristics were already suitable for RF  
438 identification after one month.

439 Other single factor effects (tag type, antenna polarization, spacer presence/absence) and their  
440 interaction were significant for  $P < 0.05$ . The statistical model coefficient  $R^2$  was equal to  
441 0.92. Means for the tag type factor were divided into homogeneous sub-sets by means of the  
442 post-hoc *Tukey* test as indicated by the different letters in Table 5.

443 Fig. 6 illustrates by means of box plots the distribution of  $P_{min}$  values, comparing the antenna  
444 type (linear or circular polarized) and the transponder type factors.



445 Considering the interaction between tag types and antenna polarization factors, all tag types  
446 resulted more or less easily identified (thus requiring a lower  $P_{min}$ ) by means of the polarized  
447 linear reader antenna. The power required for the activation of tag  $n$  was also very low on  
448 the cheese and the low variability and high significance of the results in the Tukey test  
449 encourage the use of this tag both with circular and linear polarization antennas.

450 On the contrary, the use of tag  $p$  on the cheese should be avoided as mean  $P_{min}$  values were  
451 the highest and a strong variability was observed, especially in the case of the circular  
452 polarization antenna.

453 Means of the dependent variable  $P_{min}$  for tags  $o$  and  $r$  were not significantly different in the  
454 Tukey test, but the effect of field polarization was not the same. For tag  $o$ , which is a double  
455 dipole, the mean data for the circular and linear antennas were similar, but the linear  
456 polarized field affected good repeatability of the data. On the contrary, for tag  $r$ ,  $P_{min}$  values  
457 were lower and less dispersed in the case of the linear polarization antenna.

458 The presence of a plastic spacer between tag and cheese face significantly decreased the  
459 required power for correct tag functioning (Fig. 7). This is probably due to the fact that the  
460 insertion of an electromagnetic inert material between the tag antenna and the cheese surface  
461 could overcome the effects of gain penalty and antenna detuning (Lorenzo *et al.*, 2011;  
462 Dobkin and Weigand, 2005). In particular, the presence of the spacer clearly improves tag  $p$   
463 readability by a strong reduction of  $P_{min}$ . For this tag, the presence of the spacer also led to  
464 the reduction of data variability in comparison to the  $P_{min}$  values measured without the  
465 spacer.

466 Generally, the spacer allowed  $P_{min}$  reduction for all the considered tags, except in the case of  
467 tag  $n$  for which the activation power remained constant both with and without the spacer,  
468 even if without the spacer a higher variability was observed.

469

## 470 **5. Proposed reading methods at strategic points in the cheese production process**

471

472 The results reported in the previous section led to the definition of a layout for an RFID  
473 traceability system, which is reported on the right-side of Fig. 1. The system design  
474 guarantees item-level RFID identification of single cheese wheels by tracking their  
475 movements along the whole production process. At the beginning of daily production, the  
476 traceability software links information about the TU “dairy milk lot” to the cheese

477 processing parameters. The TU “cheese lot”, comprehensive of all the cheese wheels  
478 produced during the day, is thus formed. All the cheese wheels of such lot share this initial  
479 information. At this point, each single cheese wheel, identified by a unique code number  
480 jointly stored in the affixed tag (LF, HF or UHF) and in the dairy factory data base,  
481 constitutes a new TU that inherits the “cheese lot” information. The information concerning  
482 the specific path followed by each single cheese wheel in the next phases (ripening etc.) will  
483 be stored at item level. During tag application, an additional phase can be considered in  
484 order to crosscheck the tag code. The HF and LF transponders resulted already readable by a  
485 PDA immediately after application on the curd. On the contrary, due to the high water  
486 content, UHF technology is not suitable for cheese identification during the earlier cheese  
487 making process phases. Unlike traditional food traceability systems, where during some  
488 operation on raw or bulk materials the paper identifier must be physically separated from the  
489 product, engendering potential traceability errors, the tag assures the reliability of single item  
490 tracking. At this stage, traceability can be guaranteed by tracking the single item movements  
491 by means of static and dynamic RFID identification stations. To register the transfer into  
492 storage, cooling or ripening rooms, handheld devices as well as static RF readers can be  
493 envisaged.

494 By handheld device, the use of a portable loop antenna that could be inserted between two  
495 adjacent shelves facilitates the reading of the tag both on the face and on the edge of the  
496 cheese wheels (see Fig. S3, on the left), while the PDA alone allows only the detection of  
497 tags on the edge (Fig. S3, on the right). Single wheel identification could also be performed  
498 in the ripening rooms by using devices like the proposed cutting board, but this could be  
499 practically carried out only if paired with other operations, as for instance brushing,  
500 performed either automatically or manually.

501 The simultaneous and multiple identification of several food items should be very useful in  
502 updating the inventory without human intervention. For this purpose, fixed RFID systems  
503 could be integrated with equipment used for handling. An LF or HF panel antenna, for  
504 instance, could be integrated in the trolley used to transport the cheese by using the same  
505 method (loop antenna) proposed for the cutting board, simply by adapting the antenna  
506 dimensions to the number, the position and the shape of the collected items.

507 Multiple dynamic identification is usually applied in logistics to simultaneously identify  
508 several objects transiting through a gate, whose width ranges between 2 – 2.5 m, allowing  
509 the passage, for instance, of a trolley transporting a pallet.

510 For cheese wheels however, considering the coverage of the antennas, the HF and UHF  
511 portal width should not exceed 1 m, which is problematic for trolley transit. With an HF gate  
512 composed of two antennas, the tags can be identified even through one or two cheese wheels  
513 but, in our experience, the speed should be very low (not exceeding  $0.2 \div 0.4 \text{ ms}^{-1}$ ).

514 Using UHF systems in the food industry implies reading difficulties which can be overcome,  
515 for example, with a good position of the items with respect to the receiving antenna. To  
516 obtain good readability, the options of applying tags on the cheese wheel edge or on its face,  
517 has to be evaluated during the whole process by considering the optimal orientation during  
518 handling and transport on trolleys, belts, etc.

519 To reduce rind ruptures and limit the unwanted development of mould under the tag,  
520 positioning the transponder between two casein disks was found to be the most suitable  
521 solution for single cheese wheel identification. The tags remain well inserted in the cheese  
522 rind even after repeated brushing phases. The use of two casein disks limits cheese surface  
523 damage during the tag-recovering phase, which can be performed at any time, typically at  
524 the end of the supply chain, depending on the customer requests. A first option for cheese  
525 tracking is to remove, sanitize and recycle the tag. In this case, at the weighing, cutting and  
526 packaging station, the last RFID identification of the cheese wheel occurs before removing  
527 the tag and the traceability information is then linked to other types of cheaper identifiers  
528 (bar code, label, an additional and cheaper tag, etc.) which will reach the consumer (see Fig.  
529 S6 on the right). Another option in food traceability is to leave the transponder on the  
530 product till the point of sale. In this case, tag recycling is more difficult and the use of  
531 disposable low-cost tags is recommended.

532 In the case of cheese, the tag or the casein disk should be brightly coloured thus helping  
533 visual detection in order to remove the tag without risk of swallowing by the consumer.

534 Tag persistence must be preliminarily evaluated in function of the tag application methods:  
535 the use of only one casein disk positioned on the tag (see Fig. S1, on the left), which was  
536 directly applied on the cheese surface, enhances tag persistence on the external cheese  
537 surface but it was observed that this option promotes mould formation on the cheese rind.  
538 Conversely, when the tag was included in two casein disks, mould formation on the rind was

539 prevented and, especially in the case of small tags, the visual impact of the small hole left on  
540 the rind was minimal (see, for instance, the case of tag *c*, Fig. 8, on the right).

541 Recent literature on RFID systems for cheese traceability reports that, on the contrary, other  
542 tag types which are anchored to the cheese by a plastic screw, caused ruptures in the rind  
543 which led to mould developing during ripening, altering cheese quality (Papetti *et al.*, 2012).

544

## 545 **6. Conclusions and future research directions**

546

547 RFID systems can be exploited for single matured cheese wheels electronic identification,  
548 reducing the traceability unit size and lowering the granularity of the tracing system. In  
549 particular, identification reliability by an RFID transponder was assessed for a pressed and  
550 long-ripened PDO cheese. Tags resulted apt to resist to the environmental conditions and to  
551 the operations typically performed in ripening rooms. Product quality wasn't affected by tag  
552 insertion. Cheese presence strongly influences the reading zone, especially at higher  
553 frequencies (UHF band) and in the first processing phases when cheese water content is  
554 high.

555 For this reason, before introducing an RFID system for tracking cheese, an accurate  
556 evaluation of the technical solutions should be compared in terms of frequency band and  
557 tag/antenna coupling to track the cheese in different situations: for this purpose, the  
558 operations which must be tracked, structural limits, environmental conditions and cheese  
559 composition, which continuously evolves during the process, must be considered.

560 The systems which proved more suitable for identification of the single TU through all the  
561 considered phases in the tracking path were those operating in the HF band, which can be  
562 used by handheld or mobile devices and in fixed stations, where antennas are easily adapted  
563 to structures and procedures performed at each tracking point. However, with the HF  
564 systems employed in this paper, dynamic and/or multiple identification can be performed  
565 only by modifying the methods used in routine cheese processing operations such as, for  
566 example, cheese wheel positioning, trolleys speed and gates width. Physical and  
567 microbiological damage to the cheese rind proved minimal for the smaller HF tag if  
568 compared with other tags.

569 When adopting LF technology, in order to obtain equal reading distances, the transponder  
570 size should be increased by widening the shape of the hole after transponder removal, which

571 could lead to a major risk of mould formation on the cheese rind and visual alterations which  
572 might not be appreciated by the consumer. LF systems did not prove suitable with dynamic  
573 and multiple cheese wheels tracking in the considered production process.

574 UHF systems are not suitable for cheese wheels identification during the cheese production  
575 process as the signal can be transferred from tag to reader only during ripening, warehousing  
576 and distribution. This implies that the choice of a UHF system should especially regard cases  
577 where the tag is delivered to the point of sale, attached to the cheese wheel.

578 The integration of a UHF identification system in dairy factories implies a very careful  
579 selection of both reader and tag type as well as the assessment of good practice methods for  
580 reliable reading rates. The study allowed to conclude that the successful integration of an  
581 RFID system in a food production process depends on multiple factors related not only to the  
582 RFID devices features, but also to the production process layout.

583 The costs/benefits ratio in the implementation of an RFID system is difficult to estimate.  
584 While fixed and variable costs are normally available, the challenge is to quantify benefits  
585 that are more or less hidden in the production process and along the whole supply chain. For  
586 instance, advantages due to labour reduction, automation, transparency in inventory  
587 locations, lower risk of inventory shortage, the risk to overpass the ripening period thereby  
588 altering quality, easier supply chain management, improved logistics organisation and  
589 availability of real time synchronized data are hidden in the process and difficult to quantify  
590 (Kumar *et al.*, 2011).

591 Considering the two options envisaged in the proposed RFID system for single cheese wheel  
592 traceability involving tag recycling or cheese tracking till the point of sale, preliminary cost  
593 analysis should be performed by considering LF, HF or UHF systems. Variable costs can be  
594 contained by recycling transponders using covering materials that can be sanitized and  
595 reattached to another cheese wheel.

596 In this case, the information is linked to the whole cheese wheel or to the packed cuttings by  
597 a cheaper identifier such as an optical code or an RFID at a lower cost (UHF).

598 In perspective, future research should be carried both to further improve the system  
599 performance and reliability for ripened cheese wheels as well as to extend the RFID  
600 technologies implementation to other cheese types.

601 The improvement of UHF tags and the design of inlays that minimize RF transmission  
602 inefficiency due to the contact with the cheese could enhance the overall system  
603 performance at lower costs.

604 Finally, a well-assessed costs/benefits analysis should be performed for the introduction of  
605 RFID in cheese traceability at item level and lot level by verifying the potential added value  
606 to the supply chain.

607

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609

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612

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790 **Notation**

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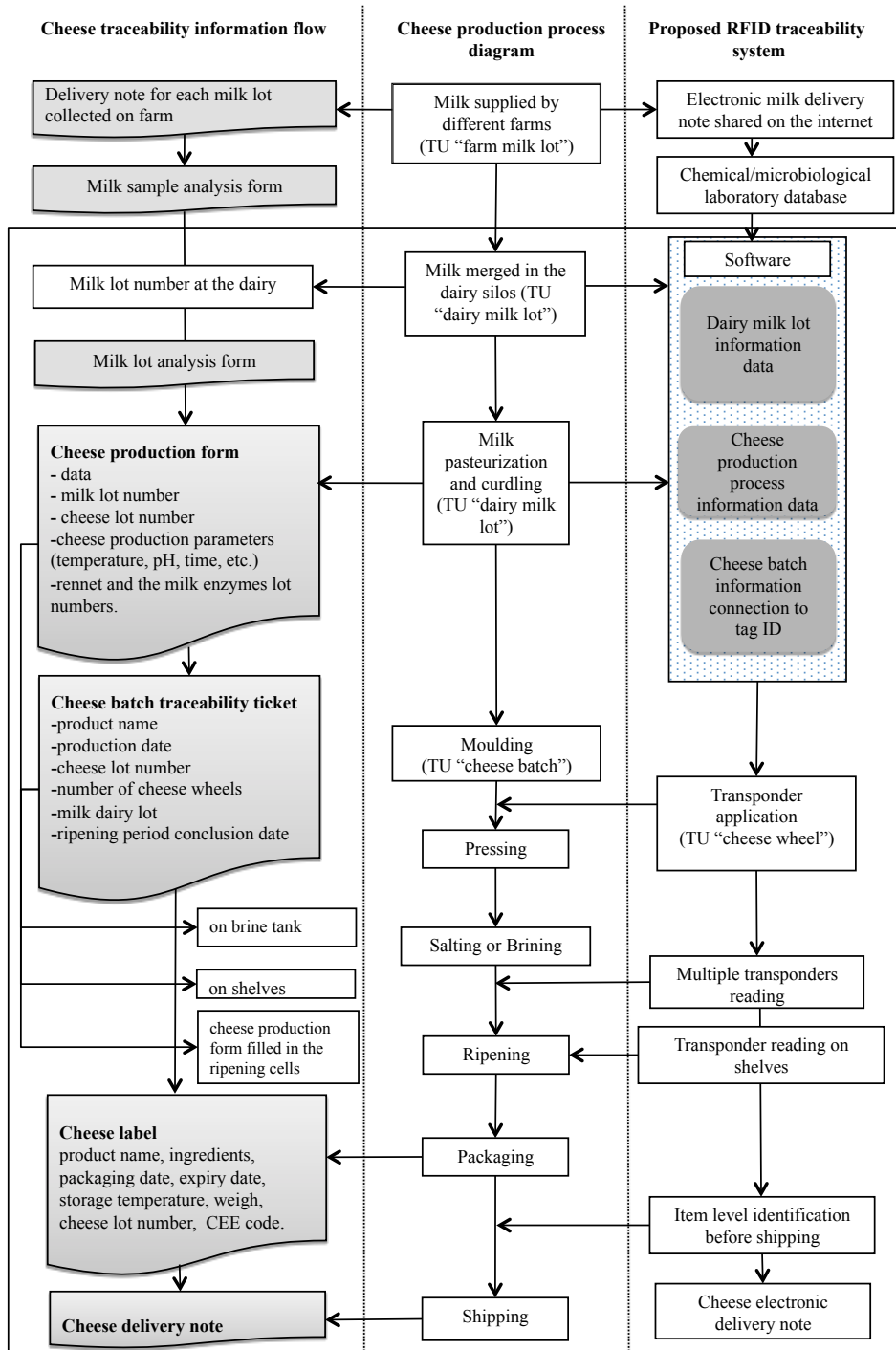
$\lambda$	Wavelength [m]
DAT	Dynamic Antenna Tuner
$D_{max}$	Maximum reading distance [m]
$Dr\%$	Tag detection rate defined as the ratio of number of successful identifications on the total number of tests (100 repetitions per trial).
EPC	Electronic Product Code
GLM	Generalized Linear Model
HF	High Frequency
ID	Identification number of tag (ISO18000-6C compliant)
ISO	International Organization for Standardization
$L_b$	Distance from the centre to pole of the HF cutting board reading area with tag in parallel configuration [m]
LF	Low Frequency
PA6	Polyamide 6 ( <i>Nylon</i> )
PDA	Personal Digital Assistant
PDO	Protected Designation of Origin
PET	Polyethylene terephthalate
$P_{min}$	Minimum TPO requested to activate and read the ID tag [W].
$R_a$	Equatorial radius of the HF cutting board reading area with tag in parallel configuration [m]
$R_c$	Distance between the HF cutting board centre and the external limit of the torus reading area [m]
$R_d$	Major radius of the HF cutting board reading area (m) with tag in perpendicular configuration
$R_e$	Minor radius of the HF cutting board reading area with tag in perpendicular configuration [m]
RFID	Radio-Frequency IDentification
TPO	Transmitter Power Output [W]
TU	Traceability Unit
UHF	Ultra High Frequency
UNIANOVA	In statistics, one-way analysis of variance

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Figures

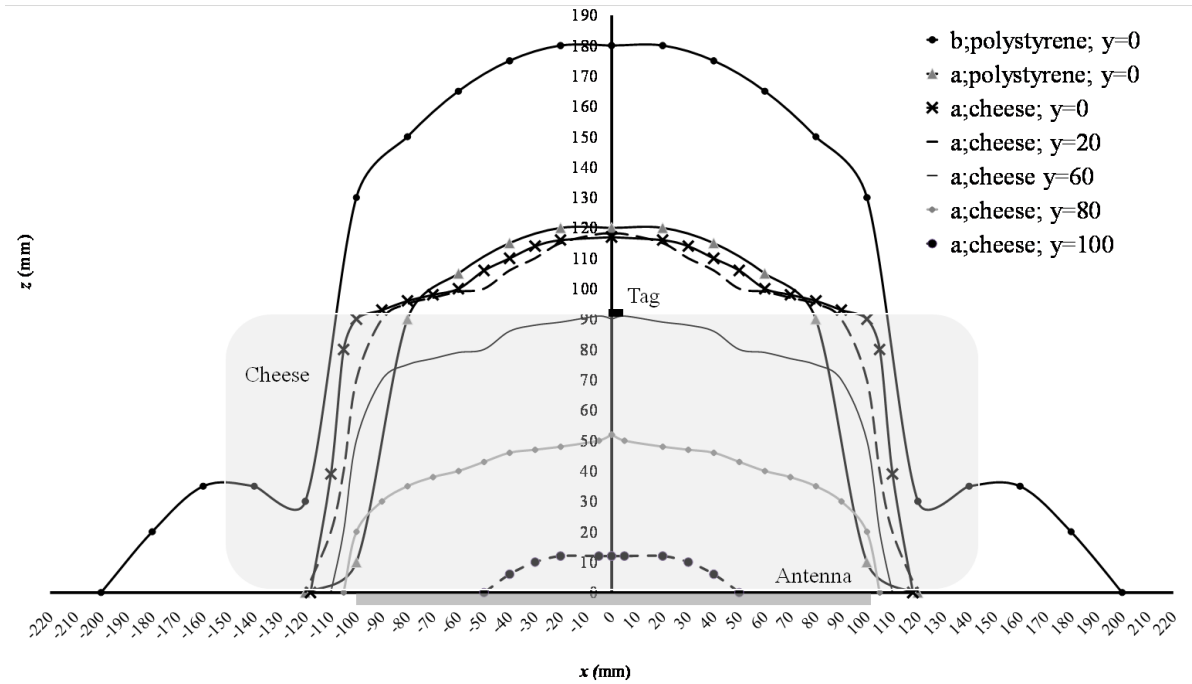


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797 Fig. 1. The current production flow chart at the dairy (in the middle), the traceability  
 798 information flow (on the left) and the proposed RFID traceability system (on the right).

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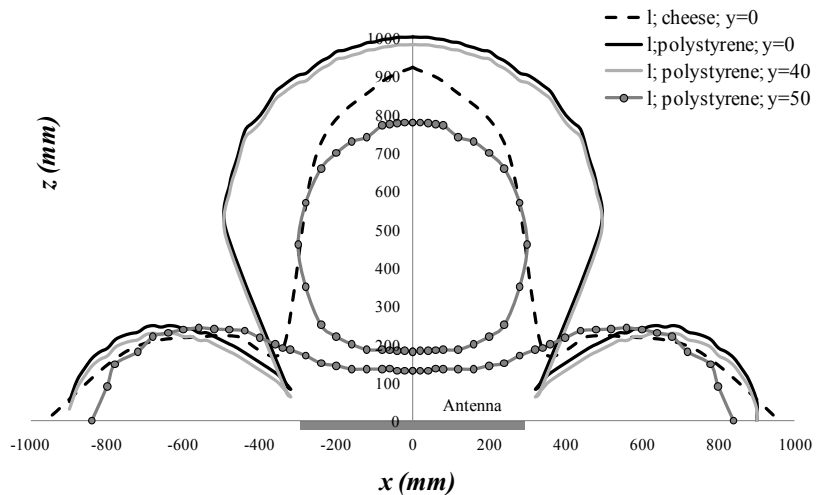
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802 *Fig. 2. Reading zone xz cross-sections of the LF (125 kHz) panel antenna for tag 'a' (INTAG*  
 803 *200) and 'b' (INTAG 300). Tags were applied on cheese surface in parallel orientation. To*  
 804 *evaluate the effect of cheese, the reading volume cross-sections with tags applied on the*  
 805 *polystyrene support are also reported.*

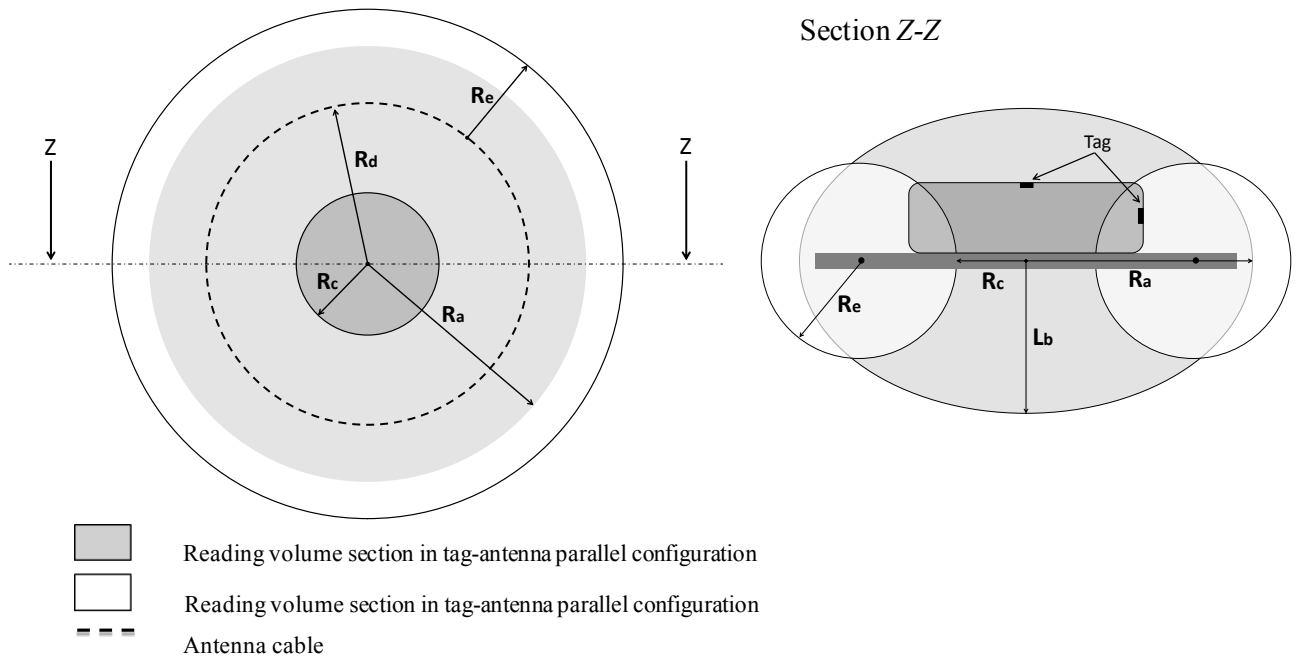
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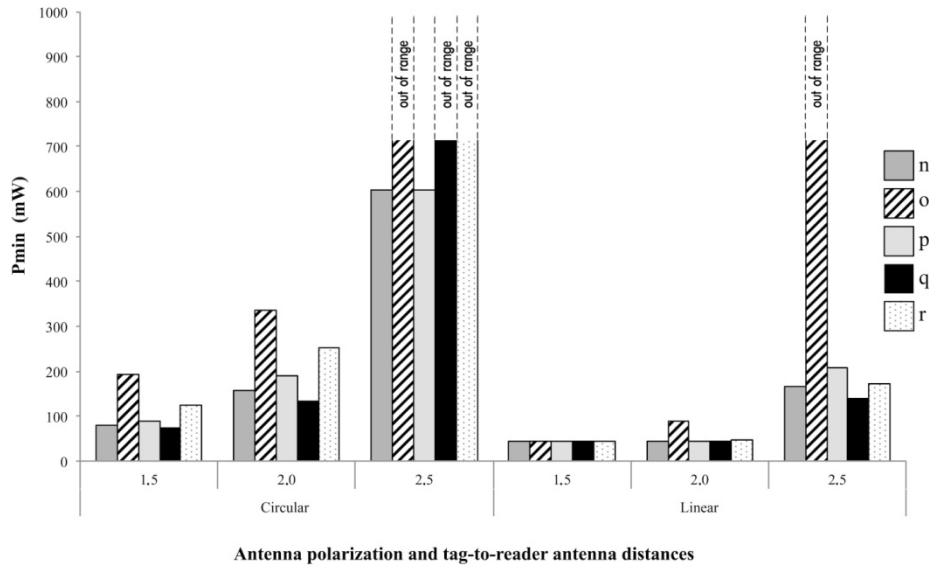
809 *Fig. 3. Reading volume  $xz$  cross-sections of HF Obid-i-Scan antenna using tag '1' applied on*  
 810 *cheese surface in parallel orientation with respect to the antenna plane. Results with tag on*  
 811 *polystyrene support are also reported as reference.*  
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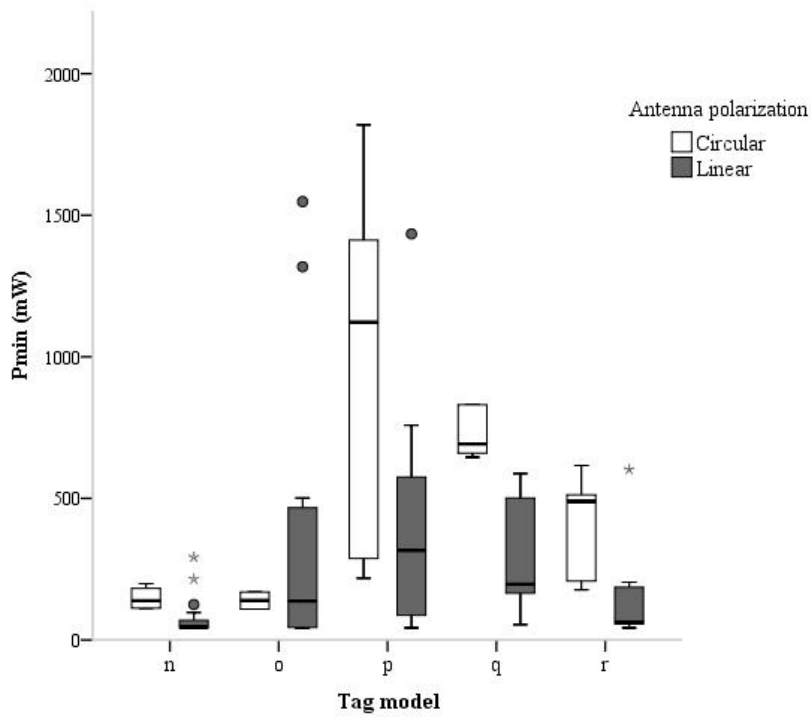
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814 *Fig. 4. Cutting board for HF identification of cheese wheels. Reading volume section*  
 815 *determined with tag 'c' applied on the cheese face (in parallel orientation) or on the cheese*  
 816 *outer edge (in perpendicular orientation) are reported.*  
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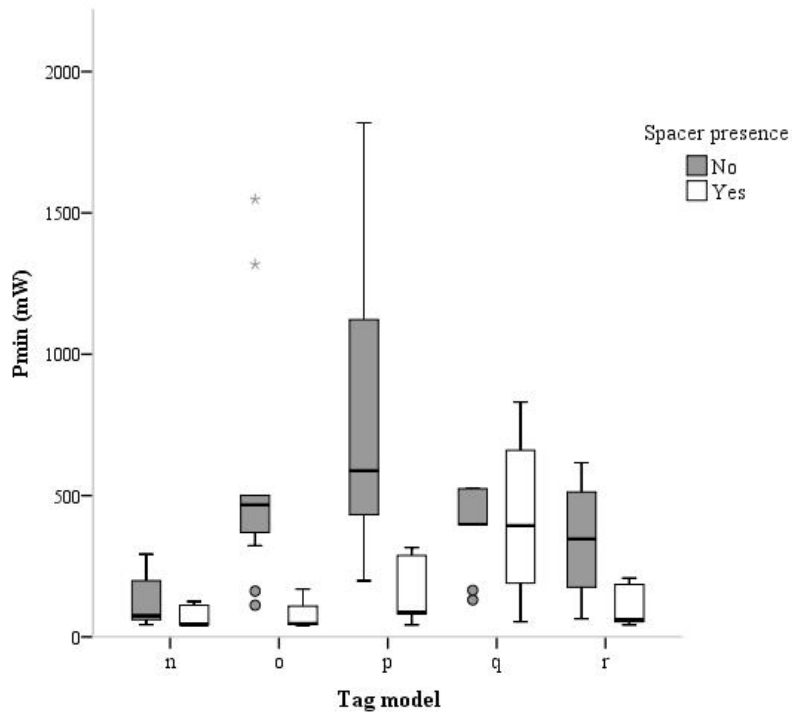
820  
 821 *Fig. 5. Minimum power ( $P_{min}$ ) required for tag activation at different tag-to-reader antenna*  
 822 *distances (m) with linear and circular polarized antennas. Tags were applied on a*  
 823 *polystyrene support.*  
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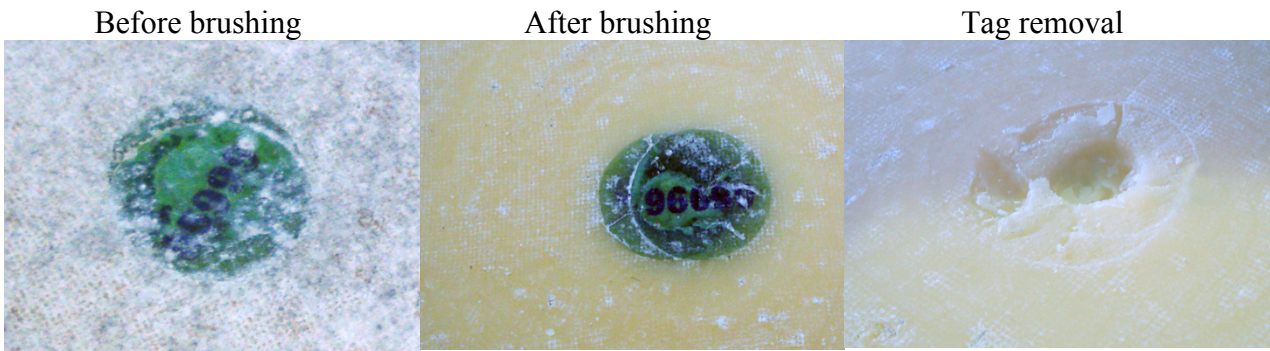


826 Fig. 6. Box plot of distribution of  $P_{min}$  values for antenna polarization and tag type factors,  
 827 when tags were applied on cheese surface. Tag-to-reader antenna distance was set to 0.5 m.  
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830  
 831 Fig. 7. Box plot of distribution of  $P_{min}$  values for “spacer presence” and “tag type” factors,  
 832 when tags were applied on cheese face. Tag-to-reader antenna distance was set to 0.5 m.  
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837 *Fig. 8. Cheese wheel and transponder aspect before and after the brushing phase (on the left*  
838 *and at the centre, respectively) and the tag removal (on the right).*

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**Tables**856 *Table 1. RFID transponders used in cheese factory and in laboratory trials. For each tag*857 *operating frequency, tag type, producer, model, shape, coil size, tag thickness, material and*858 *chip type are reported.*

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<i>Operating frequency</i>	<i>Tag type</i>	<i>Producer</i>	<i>Model</i>	<i>Shape</i>	<i>Coil size (mm)</i>	<i>Tag thickness (mm)</i>	<i>Covering Material</i>	<i>Chip type</i>
LF 125 kHz	<i>a</i>	Sokymat	INTAG 200	Circular	Ø = 20.0	2.5	PA6 Modified	Unique
	<i>b</i>	Sokymat	INTAG 300	Annulus	Ø = 30.0	2.5	PA6 Modified	Hitag S
HF 13.56 MHz	<i>c</i>	Sokymat	Logi Tag 161	Circular	Ø = 16	2.9	Modified thermoplastic	Philips I-Code SLI
	<i>d</i>	UPM Raflatac's	MiniTrack	Rectangular	14 x 31	0.15	Adhesive paper card	Philips I-Code SLI
	<i>e</i>	-	-	Circular	Ø = 32	0.1	Modified thermoplastic	-
	<i>f</i>	LAB ID	K.M9. 2.5 A	Rectangular	19 x 38	0.15	PET	Philips I-Code SLI
	<i>g</i>	-	-	Circular	Ø = 24	0.65	Modified thermoplastic	-
	<i>h</i>	-	-	Annulus	Ø = 88	0.3	Modified thermoplastic	-
	<i>i</i>	LAB ID	K.M. 1.5 BV3	Rectangular	24 x 59	0.3	PET	Philips I-Code SLI
	<i>l</i>	LAB ID	IN523	Rectangular	45 x 76	0.65	PET	Philips I-Code SL2 ICS20
	<i>m</i>	GAO RFID	Paper label 113002	Square	43 x 43	0.25	Adhesive paper card	Philips I-Code SLI
UHF 865 MHz	<i>n</i>	LAB ID	UH100	Rectangular	94 x 7.8	0.15	PET	Impinj Monza 4U
	<i>o</i>	LAB ID	UH3D40	Square	40 x 40	0.1	PET	Impinj Monza 4QT
	<i>p</i>	LAB ID	UH331	Rectangular	95 x 7.2	0.15	PET	Impinj Monza 5
	<i>q</i>	ALIEN	9634	Rectangular	46 x 44	0.25	PET	Alien Higgs-3
	<i>r</i>	ALIEN	9662	Rectangular	70 x 17	0.25	Adhesive label	Alien Higgs-3
	<i>x</i>	UPM Raflatac	DogBone	Rectangular	93 x 23	0.10	Adhesive paper card	Impinj Monza 3

<i>v</i>	UPM Raflatac	Short Dipole	Rectangular	92 x 11	0.15	Adhesive paper card	NXP U-Code
<i>z</i>	UPM Raflatac	Frog	Square	68 x 68	0.15	Adhesive paper card	Impinj Monza 3

860 *Table 2. Tag-to-PDA maximum reading distances (mm) with tag applied on cheese surface*  
861 *after 60 days ripening. In this table are summarized the results at LF (125 kHz), HF (13.56*  
862 *MHz) and UHF (865 MHz) frequencies.*  
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<i>Operating frequency</i>	<i>Tag type</i>	<i>Maximum reading distance (mm)</i>
LF	<i>a</i>	In contact
	<i>b</i>	70
	<i>d</i>	70
HF	<i>f</i>	50
	<i>i</i>	70
	<i>l</i>	130
UHF	<i>x</i>	40
	<i>v</i>	In contact
	<i>z</i>	130

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866 Table 3. Maximum reading distance,  $D_{max}$  (mm), between HF tag models and the OBID I-  
 867 scan Long Range antenna. Each tag was attached on the cheese wheel in different  
 868 orientations.

869 The influence of cheese presence is shown by the rate (%) of  $D_{max}$  with tag applied to the  
 870 cheese surface and the  $D_{max}$  with tag applied on the polystyrene support.

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Tag type	$D_{max}$ on polystyrene (mm)	$D_{max}$ on cheese/ $D_{max}$ on polystyrene (%)			
		Tag on the face		Tag on the edge	
		frontal	+180°	frontal	+180°
<i>c</i>	330	100%	100%	100%	100%
<i>d</i>	365	86%	79%	29%	not readable
<i>f</i>	510	93%	83%	80%	80%
<i>i</i>	775	92%	92%	39%	39%
<i>l</i>	1005	92%	92%	59%	59%
<i>m</i>	650	91%	91%	64%	54%

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888 *Table 4. Tag detection rate (Dr %) determined for six HF tag models by the HF cutting*  
 889 *board. Tag was in parallel (tag on cheese face) and in perpendicular configuration (tag on*  
 890 *the cheese wheel outer edge) with respect to the antenna plane. In case of parallel*  
 891 *configuration, test was conducted with tag in contact with the cutting board or attached on*  
 892 *the opposite cheese face to the board. On the contrary, in case of perpendicular*  
 893 *configuration, cheese wheel was placed randomly on the cutting board surface.*

894

Tag type	DR %		
	Tag on the face		Tag on the edge
	in contact	opposite side	random, perpendicular
<i>c</i>	100	100	78
<i>e</i>	100	100	0
<i>f</i>	100	100	89
<i>g</i>	100	100	93
<i>i</i>	100	100	100
<i>l</i>	100	100	-

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896 *Table 5.  $P_{min}$  mean values (mW) determined for the different transponder models applied on*  
 897 *cheese. All the factors effects considered in the statistical model were included in the mean*  
 898 *calculation. The letters (a-d) indicate the homogeneous sub-sets for Tukey test at  $P < 0.05$ .*  
 899 *Tag-to-reader antenna distance was set to 0.5 m.*

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Tag type	Mean $P_{min}$ (mW)	Tukey subset	Number of readings	SD	Minimum $P_{min}$ value (mW)	Maximum $P_{min}$ value (mW)
<i>n</i>	90.79	a	30	53.31	40	199
<i>o</i>	217.41	b	22	187.34	43	501
<i>r</i>	242.61	b	33	193.90	48	616
<i>q</i>	457.33	c	24	235.81	158	831

<i>p</i>	600.69	<i>d</i>	47	492.43	81	1819
Total	350.78		156	363.40	40	1819

901

902 *Table 6. Statistical analysis of the effect of factors and their interactions on the mean tag*  
903  *$P_{min}$  (mW) determined with tag applied on cheese surface at 0.5 m tag-to-reader antenna*  
904 *distance.*

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<b>Factor</b>	<b>DF</b>	<b>F-ratio</b>	<b>P-value</b>
Tag type	4	109.88	0.000
Antenna polarization	1	287.48	0.000
Ripening duration	1	0.38	0.845
Spacer	1	322.79	0.000
Tag type * Antenna polarization	4	31.57	0.000
Tag type * Ripening period	4	6.24	0.000
Tag type* Spacer	4	47.57	0.000

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