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 highest level of traceability efficiency in terms of quality and safety. The application of innovative systems and technologies to collect information at item or batch level at affordable costs enables manufacturing enterprises both to better control the production process and to share quality and traceability data in supply chain collaborative networks (Bechini *et al.,* 2008; Barge *et al.,* 2009). The availability of a system which could continuously update inventories at supply chain level could lead to a reduction of costs tied to high inventory-to-sales ratios (Golan *et al.*, 2004; Varese *et al.,* 2008; Costa *et al.,* 2013).

To our best knowledge, cheese traceability is currently managed at lot level and documented by written records. In the most favourable cases, the information is inserted in a local database. The application of innovative systems and technologies to automate information collection related to the single product unit could improve the performance of traceability systems (Dabbene and Gay, 2011) and optimize warehouse management and logistics (Alfaro and Ràbade, 2009), thereby reducing costs.

Moreover, by means of traceability data sharing along the whole food supply chain, food safety would be increased and, in case of a recall, product withdrawal would be very rapid. In all cases, when data sharing is put in place, privacy issues should be attentively considered and managed (Lee and Park, 2010; Jacobs, 1996; Kumar and Budin, 2006).

In the near future, due to the high risk of counterfeiting of labelled and certified products (e.g. the "made in Italy" products), new initiatives are expected to preserve the identity of valuable, high quality local products. Considering long-ripened protected designation of origin (PDO) cheese, the high value of the product is related to the preservation of credence attributes that cannot be perceived directly by the consumer, but can only be guaranteed by an effective, item-level, traceability system (Golan *et al.,* 2004). Identity preservation at item level is also important in case of special productions such as, for example, Kosher and Halal food or military supplies (Dabbene *et al*., 2013).

Single wheel identification by traditional methods (e.g. labels or brands), through the production process and during the maturing period, is critical due to cheese chemical composition (moisture, pH, fat and salt content), physical characteristics (texture, rind surface condition), environmental conditions during the different processing phases (curd moulding, pressing, dry or brine salting, ripening), and frequent product handling (e.g. daily turning, brushing and scraping during ripening).

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

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

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

The aim of this paper is to investigate the effectiveness of RFID technology in tracing single cheese wheels, from curd making to final packaging and delivery. RFID systems, operating at low, high and ultra high frequencies (LF, HF and UHF respectively), were tested and compared with the aim of evaluating the performances and limits of each solution at different stages of the production process. Performance evaluation of RFID systems requires RF measurements that have to be conducted in strictly controlled conditions (Derbek *et al.*, 2007). The dielectric properties and shape of food matrices usually affect tag reading ranges (i.e. the longest tag-to-reader antenna distance that still guarantees tag activation, data processing and answer transmission), reading zones (i.e. the region where the tag is detected) and the transmitted power required for tag activation. The reliability of RF identification needs to be evaluated for each category of food product, in the production and logistics phases as well as in the different environments.

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

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

2. Products & information flow in a dairy factory

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

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

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

For milk, TUs generated during the collecting phase are typically rather small, allowing incentive premiums on the milk price on the basis of quality parameters (e.g. pH, presence of antibiotic residues, protein and fat content, somatic cells number and total microbial count). In the considered dairy factory, a new TU – the dairy milk lot – resulting from the blending of several farm milk lots, is then defined. Here, the traceability system links information about input milk and dairy lots. From each dairy lot a batch of about 110 cheese wheels is obtained by pasteurization and curdling. Traceability information is manually noted on a form and on a paper ticket which report the milk lot, the cheese lot number and curdling parameters as well as the milk enzymes and the rennet type, the process temperatures, the pH level, the curd pieces dimensions and the type of salting. When the whey removal process is finished, the whole fresh broken curd is cut in rectangular chunks which are then placed into a circular stainless steel mould where they will be pressed for 24 hours. From this point, in the dairy traceability system, cheese lot identification is guaranteed by the cheese batch traceability ticket which reports the product type, the production date, the lot number, the number of cheese wheels in the lot, the milk lot tank number and the date of the expected end of maturing period. This ticket follows the cheese lot through all production stages.

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

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

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

3. Materials and methods

3.1 Radio-frequency identification systems

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

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

Two different handheld devices were tested for static tag reading in cheese factory trials: a PDA Psion Teklogix – Workabout PRO equipped with an LF or HF frequency range module, and an Id Isc Ant 200/200 I-Scan mobile antenna, composed of a reader worn at the waist of the operator and coupled to a square loop HF antenna (200 x 200 mm). Both devices were tested for the identification of cheese wheels positioned on shelves. LF tests were performed using a BlueBox Soltec reader (version FW 1.11) linked to a Bluebox 125 kHz panel antenna (200 x 200 x 15 mm).

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

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

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

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

Programming Interface. This application allowed measuring of the minimum tag activation power (P_{min}), defined as the minimum TPO required to activate and read the unique code contained in the tag (Rao *et al.,* 2005). This was obtained by means of a power sweep ranging from 0 to 2000 mW with 1 mW steps (Tortia *et al.*, 2012).
All the UHF devices used in the trial were EPC Class 1 Gen 2 protocol compliant.

3.2. Interrogation area and maximum reading distance assessment methods

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

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

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

The maximum reading distance D_{max} at $x = y = 0$ was also determined with the tag on polystyrene and on the cheese surface to evaluate the influence of the tag type and the feasibility of tag detection across the cheese. Towards this aim, D_{max} was also recorded after a 180 degrees rotation of the cheese wheel around the *y* axis. In this case the cheese remains interposed between the antenna and the tag.

A plastic cutting board with an embedded HF RFID antenna was designed and implemented. The reading volume of such a prototype of smart cutting board was determined in static conditions by using the *c* tag model. The tag was applied both on the cheese surface and on the outer edge respectively in parallel and perpendicular orientations to the antenna plane.

The performances of the system in dynamic conditions were evaluated by measuring the tag detection rates *Dr%*, defined as the ratio between the number of successful identifications and the total number of tests (100 repetitions per trial) which were performed manually by placing the cheese wheel on the prototype of the HF cutting board in random position (Fig. S4, on the right). The cheese was arranged on the antenna plane by ensuring the tag was inside the cutting board perimeter and then moved outside the antenna reading volume before the next repetition. The tests were performed using six RFID tag models (*c, e, f, g, i, l*).

3.3 Characterization of UHF systems for cheese electronic identification in anechoic chamber

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

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

The developed software was used to determine P_{min} at different tag-to-antenna distances. For each tag model, P_{min} was preliminarily measured with transponders applied on a polystyrene support. Then, to evaluate the effects of the presence of *Toma*, P_{min} was recorded with tags directly applied to the cheese wheels surface. Tests were carried out by using four cheese wheels belonging to two production lots: two ready for sale (60 days of ripening) and two ripened for 30 days. As the reading range was limited by the cheese, the tag-to-antenna distance was set at 0.5 m. Experiments were repeated using a 3 mm thick plastic spacer between tag and cheese, to evaluate possible reduction of the cheese absorbing effect on the RF signal.

In the experiment design, results in terms of P_{min} for all the combinations of antenna polarization (linear or circular), ripening duration (30 or 60 days), tag type (five tags), and presence/absence of a spacer between tag and cheese factors were collected and statistically analysed using SPSS® Statistics 17.0. The separate effects of the considered factors and their interactions were evaluated by one-way analysis of variance procedure (UNIANOVA) for regression and variance analysis of the dependent variable. A generalized linear model (GLM) was adopted. Means were then compared by a post-hoc Tukey test.

4. Results

4.1 Transponder persistence

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

4.2 Detection zone of fixed and handheld LF and HF systems for cheese wheels identification

The reading zone of the 125 kHz LF panel antenna is represented by its *xz* cross-sections (Fig. 2). The maximum reading distance D_{max} of tag *b* exceeded that of the smaller tag *a* by about 60 mm in the case of tags applied on polystyrene. The presence of the cheese only had a slight effect on the reading distance, as can be seen for the *y=0* cross-section for tag *a* attached on the two different materials.

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

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

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

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

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

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

When the tag was attached on the cheese face, the effect of a 180 degrees rotation around the *y* axis was null except for tags *d* and *f* which were the smallest among the rectangularly shaped ones. In that case, the presence of the cheese wheel thickness among receiving and transmitting antennas didn't affect tag antenna communication efficiency.

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

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

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

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

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

4.3 Detection rate of cheese wheels on an HF cutting board

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

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

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

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

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

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

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

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

4.5 Statistical analysis

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

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

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

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

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

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

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

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

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

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

The results reported in the previous section led to the definition of a layout for an RFID traceability system, which is reported on the right-side of Fig. 1. The system design guarantees item-level RFID identification of single cheese wheels by tracking their movements along the whole production process. At the beginning of daily production, the traceability software links information about the TU “dairy milk lot” to the cheese processing parameters. The TU “cheese lot”, comprehensive of all the cheese wheels produced during the day, is thus formed. All the cheese wheels of such lot share this initial information. At this point, each single cheese wheel, identified by a unique code number jointly stored in the affixed tag (LF, HF or UHF) and in the dairy factory data base, constitutes a new TU that inherits the “cheese lot” information. The information concerning the specific path followed by each single cheese wheel in the next phases (ripening etc.) will be stored at item level. During tag application, an additional phase can be considered in order to crosscheck the tag code. The HF and LF transponders resulted already readable by a PDA immediately after application on the curd. On the contrary, due to the high water content, UHF technology is not suitable for cheese identification during the earlier cheese making process phases. Unlike traditional food traceability systems, where during some operation on raw or bulk materials the paper identifier must be physically separated from the product, engendering potential traceability errors, the tag assures the reliability of single item tracking. At this stage, traceability can be guaranteed by tracking the single item movements by means of static and dynamic RFID identification stations. To register the transfer into storage, cooling or ripening rooms, handheld devices as well as static RF readers can be envisaged.

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

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

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

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

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

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

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

Tag persistence must be preliminarily evaluated in function of the tag application methods: the use of only one casein disk positioned on the tag (see Fig. S1, on the left), which was directly applied on the cheese surface, enhances tag persistence on the external cheese surface but it was observed that this option promotes mould formation on the cheese rind. Conversely, when the tag was included in two casein disks, mould formation on the rind was prevented and, especially in the case of small tags, the visual impact of the small hole left on the rind was minimal (see, for instance, the case of tag *c,* Fig. 8, on the right).

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

6. Conclusions and future research directions

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

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

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

When adopting LF technology, in order to obtain equal reading distances, the transponder size should be increased by widening the shape of the hole after transponder removal, which could lead to a major risk of mould formation on the cheese rind and visual alterations which might not be appreciated by the consumer. LF systems did not prove suitable with dynamic and multiple cheese wheels tracking in the considered production process.

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

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

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

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

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

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

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

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

7. Acknowledgements

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Notation

λ	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 (*Nylon*)
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

Figures

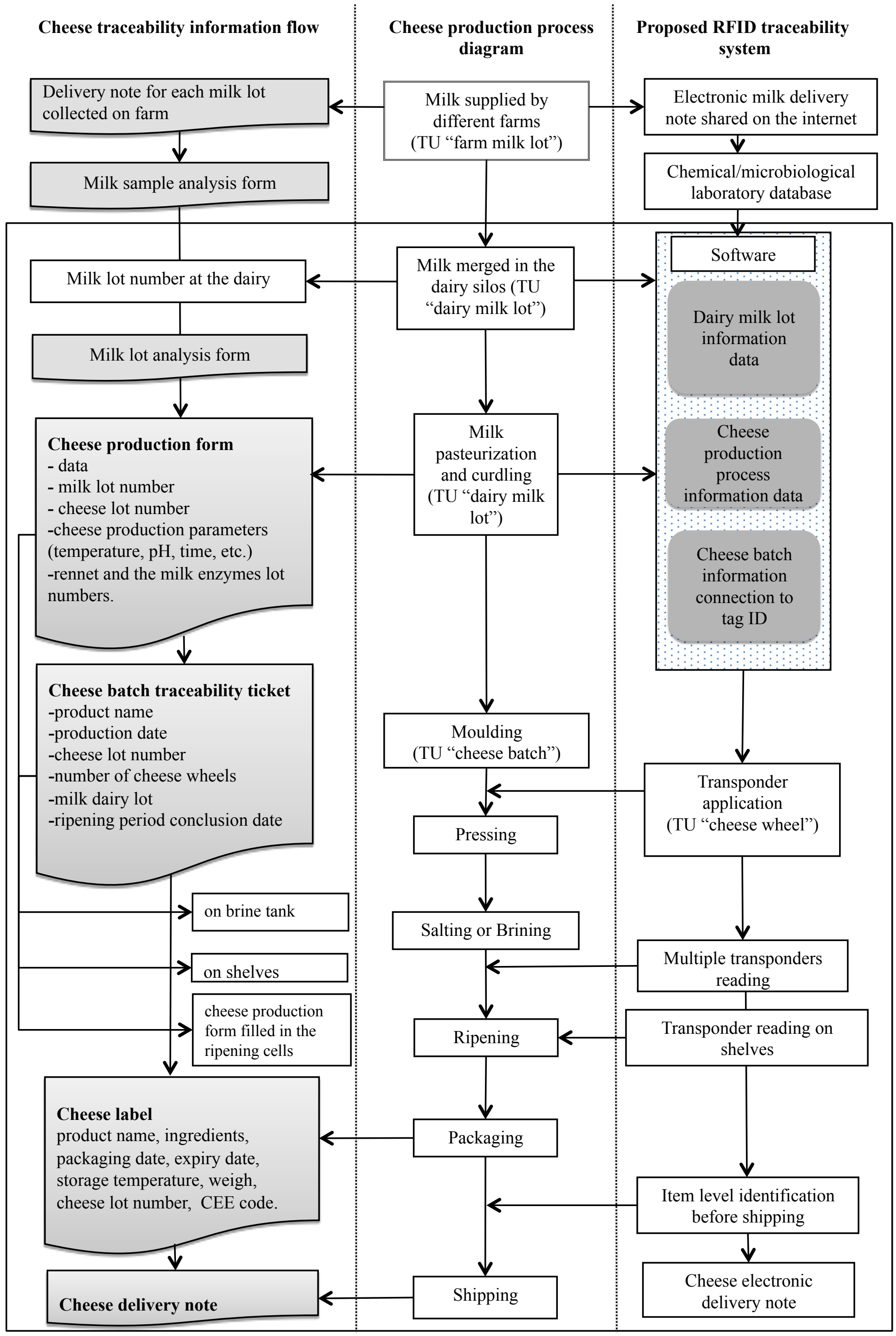

Fig. 1. The current production flow chart at the dairy (in the middle), the traceability information flow (on the left) and the proposed RFID traceability system (on the right).

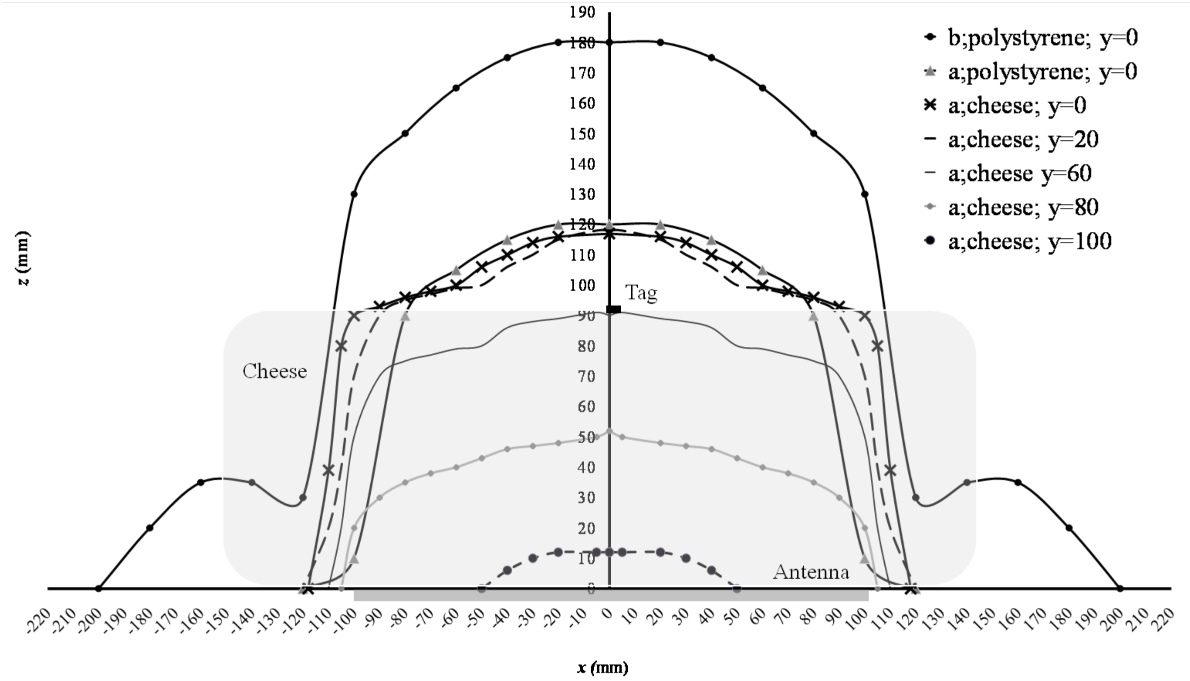

Fig. 2. Reading zone xz cross-sections of the LF (125 kHz) panel antenna for tag 'a' (INTAG 200) and 'b' (INTAG 300). Tags were applied on cheese surface in parallel orientation. To evaluate the effect of cheese, the reading volume cross-sections with tags applied on the polystyrene support are also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

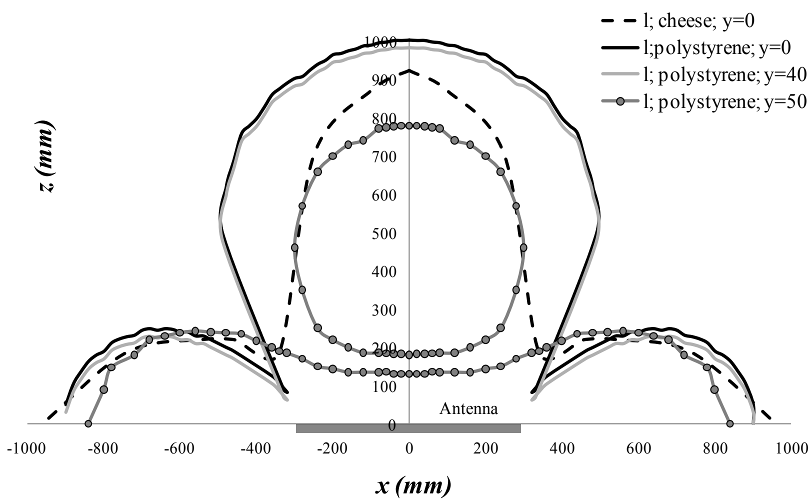

Fig. 3. Reading volume xz cross-sections of HF Obid-i-Scan antenna using tag 'l' applied on cheese surface in parallel orientation with respect to the antenna plane. Results with tag on polystyrene support are also reported as reference.

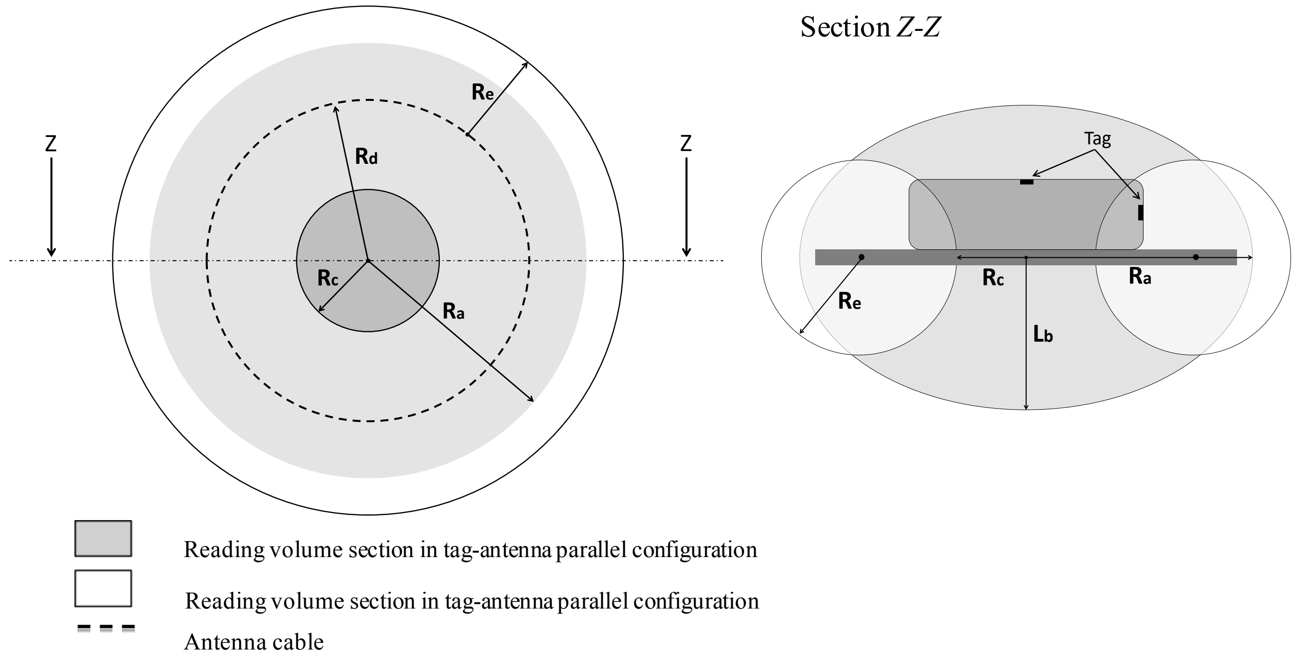

Fig. 4. Cutting board for HF identification of cheese wheels. Reading volume section determined with tag 'c' applied on the cheese face (in parallel orientation) or on the cheese outer edge (in perpendicular orientation) are reported.

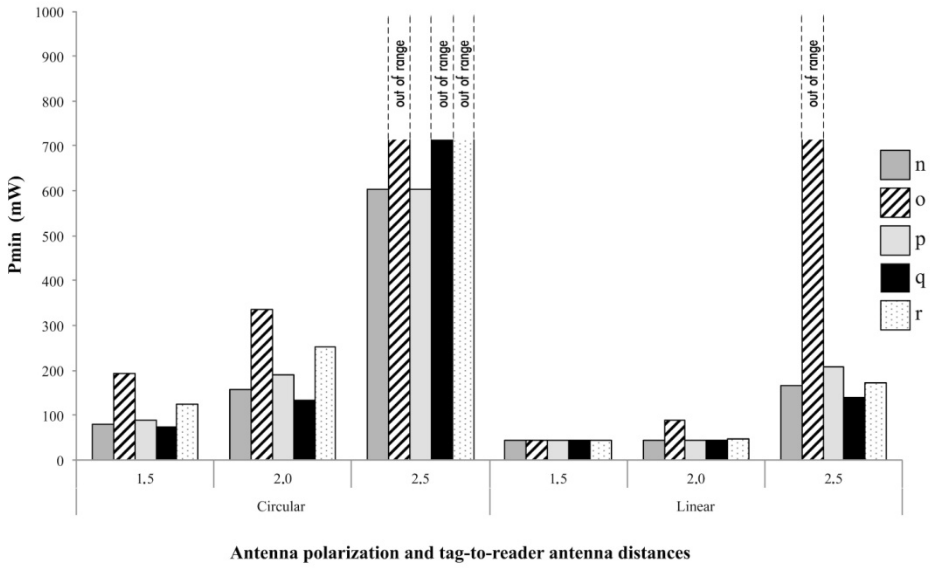

Fig. 5. Minimum power (P_{min}) required for tag activation at different tag-to-reader antenna distances (m) with linear and circular polarized antennas. Tags were applied on a polystyrene support.

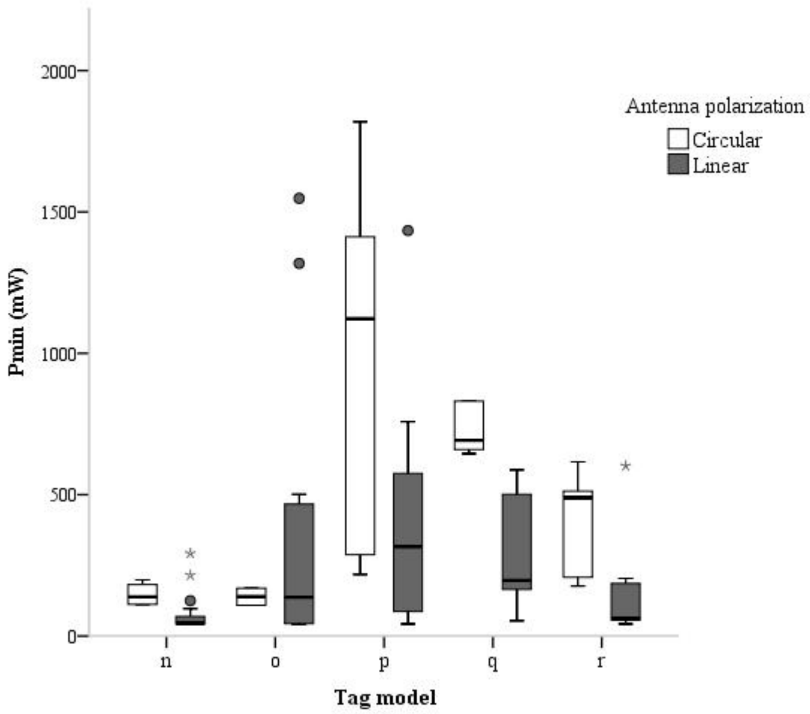

Fig. 6. Box plot of distribution of P_{min} values for antenna polarization and tag type factors, when tags were applied on cheese surface. Tag-to-reader antenna distance was set to 0.5 m.

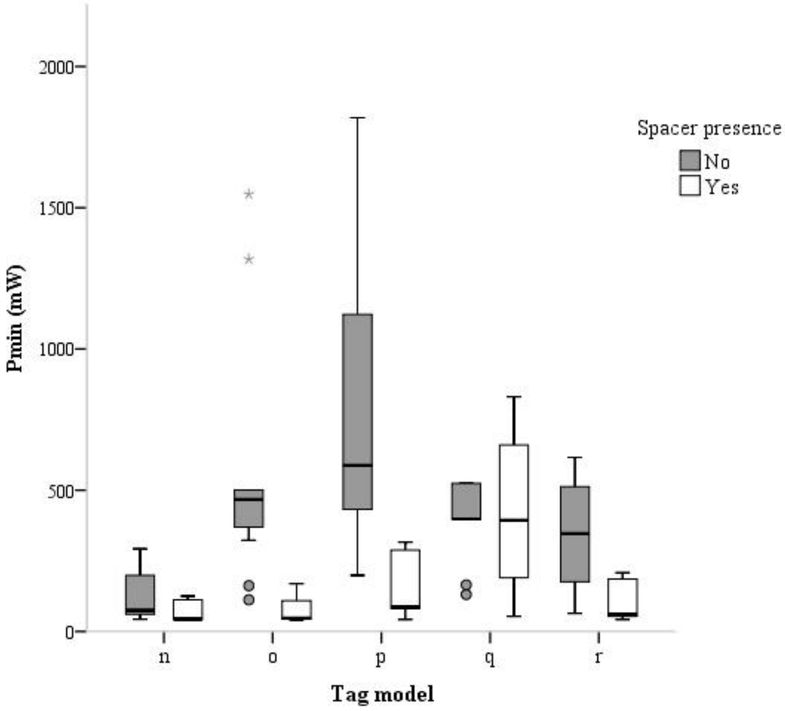

Fig. 7. Box plot of distribution of P_{min} values for "spacer presence" and "tag type" factors, when tags were applied on cheese face. Tag-to-reader antenna distance was set to 0.5 m.

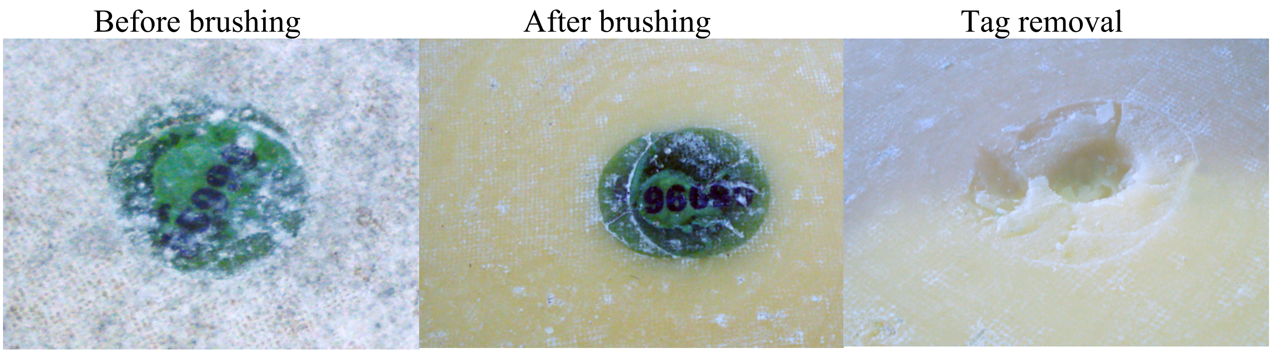

Fig. 8. Cheese wheel and transponder aspect before and after the brushing phase (on the left and at the centre, respectively) and the tag removal (on the right).

Tables

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

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

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

Table 2. Tag-to-PDA maximum reading distances (mm) with tag applied on cheese surface after 60 days ripening. In this table are summarized the results at LF (125 kHz), HF (13.56 MHz) and UHF (865 MHz) frequencies.

Operating frequency	*Tag type*	*Maximum reading distance (mm)*
LF	*a*	In contact
	b	70
HF	*d*	70
	f	50
	i	70
	l	130
UHF	*x*	40
	v	In contact
	z	130

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

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

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°
c	330	100%	100%	100%	100%
d	365	86%	79%	29%	*not readable*
f	510	93%	83%	80%	80%
i	775	92%	92%	39%	39%
l	1005	92%	92%	59%	59%
m	650	91%	91%	64%	54%

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

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

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

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

p	600.69	d	47	492.43	81	1819
Total	350.78		156	363.40	40	1819

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

Factor	**DF**	**F-ratio**	**P-value**
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