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An alternative approach to control the oxygen permeation across single-dose coffee capsules

Carlo A. Cozzolino, S. Pozzoli, S. La Vecchia, L. Piergiovanni, S. Farris*

DeFENS, Department of Food, Environmental and Nutritional Sciences, Packaging Division – University of Milan, Via Celoria 2, 20133 Milan, Italy

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ABSTRACT

The objective of this study was to investigate the potential of a hybrid coating made of pullulan and a silicon-dioxide precursor to act as an oxygen barrier on polypropylene (PP) capsules used for single-dose ground coffee. PP capsules were first treated by an oxidizing flame to allow better adhesion of the water-based coating solution. The barrier performance of the capsules (uncoated and coated) was assessed by a non-invasive approach based on fluorescence quenching. The deposition of the coating (approximately 7.0 μm thick) led to a dramatic decrease in the oxygen permeation across empty capsules at 40 °C and 25% RH (uncoated capsules: 496.91 mL [package 24 h atm]$^{-1}$; coated capsules: 14.01 mL [package 24 h atm]$^{-1}$). In the presence of coffee inside the capsules, the barrier performance was even improved (pack permeability 1.87 mL [package 24 h atm]$^{-1}$), which was ascribed to the residual oxygen inside the capsules at the beginning of the analysis. At 66% RH, the hybrid coating, while still acting as a good barrier, partially lost its performance due to the simultaneous swelling of the polymer matrix and the presence of fractures on the coating surface. The approach presented in this work can present opportunities for an alternative design of the packaging intended for coffee capsules, with a potential advantage also from an environmental perspective represented by the upstream reduction in the use of plastics.

1. Introduction

The world coffee production through the five-year period of 2008–2013 has experienced a steady increase from approximately 128.5 million bags to around 145.7 million bags, with Brazil being the largest producing country with 49.1 billion bags (ICO, 2014). In 2012, USA accounted for the largest import trade (22.2 billion bags), while the EU import totaled 40.6 billion bags (ICO, 2015). A bag is here intended as a 60 kg (i.e., 132.276 pounds) of coffee.

The driving force behind this increasing trend has been identified in the deep changes that have occurred in the supply chain over the last decade (Tozzi, 2007). Indeed, an increasing number of stakeholders have pushed toward new solutions concerning both brewing techniques and packaging systems and devices. As far as the brewing techniques are concerned, ‘‘moka’’ pots and bar machines are the most widespread solutions. Though ‘‘moka’’ machines still prevail over bar machines in some countries where the ‘‘old-style’’ consumption is conspicuous (e.g., Italy), the overall trend indicates that there is an increasing number of bar-like machines for the domestic consumption of coffee. Concurrently, new kinds of packaging devices have emerged to fulfill increasing customers’ needs, such as high quality and convenience. Pod and capsule systems, in particular, have recently gained market

* Corresponding author. Tel.: +39 0250316654; fax: +39 0250316672.
E-mail address: stefano.farris@unimi.it (S. Farris).

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share (Parenti et al., 2014). Capsules, besides being user-friendly, offer some advantages over cellulosic pods because of additional control over detrimental phenomena, such as moisture and oxygen permeation. In addition, capsules ensure the producers against the sophistication of the powder composition (e.g., the addition of lower-quality powders), thereby preserving the quality attributes of the ground coffee (e.g., aroma profile, foaming attitude, etc.) at a pre-fixed standard level.

Several kinds of capsules have penetrated the market over recent years, all of them falling into two main categories: aluminum and plastic capsules. Aluminum capsules represent the best solution for the quality preservation of coffee powder, as aluminum is a total barrier against light, gases, and water vapor. However, this material suffers high costs (base metal price ~ 1.6–1.9 €/kg) (Indexmundi, 2015; InvestmentMine, 2015) and low environmental performance, which is mainly due to the high energy consumption throughout the production process (De Schrynmakers, 2009). This aspect is partially counterbalanced by the theoretically 100% recyclability of aluminum capsules. However, the lack of dedicated facilities still limits their recycling. To address this issue, some brands have recently introduced a special recycling zone within the retail stores, with apparently increased recycling efficiency (CiAl, 2014).

Plastic capsules are mostly made of polypropylene (PP), which is a cheap material (homopolymer's price: 0.26–0.35 €/kg) (The Plastics Exchange, 2015), more suitable to processing operations (e.g., injection molding, thermoforming) compared to other polymers, such as polyethylene terephthalate (PET) due to its thermal properties. In some cases, the bottom and the top of the capsule are made of PP. In other circumstances, the top of the capsule is a lid of an aluminum foil/polyethylene bi-layer. The main issue related to plastic capsules lies in the poor oxygen barrier properties of PP (Mount, 2009). To overcome this drawback, some companies use a layer of ethylene vinyl alcohol (EVOH) sandwiched between two PP layers. More recent advances account for the incorporation of active particles with specifically developed oxygen scavenging functions. In either case, due to both technical and performance aspects, the primary packaging does not warrant adequate protection against oxygen, thus making necessary a secondary packaging, which most often consists of a two (or more)- serving bag made of a laminated structure, including PE as inner layer (~100 μm), a middle layer of aluminum foil (~7 μm), and an outer PET film (~12 μm) (Büsser & Jungbluth, 2009).

One of the threats associated with the increasing usage of capsules is the environmental impact of the large mass of packaging materials involved. Indeed, capsules are not perceived as environmentally friendly by many consumers, which makes their waste disposal one of the most urgent aspects that needs to be addressed in the next few years. Besides focusing on the end-of-life disposal, another approach is to make the selection of different packaging systems based not only on the shelf-life extension perspective but also on the packaging mass reduction goal (De Monte, Padoano, & Pozzetto, 2005). As pointed out by Brommer, Stratmann, and Quack (2011), packaging materials play a crucial role in the definition of the carbon footprint of different coffee products. The same authors stated that the environmental impact of capsule-based coffee machines is the highest compared to other methods (e.g., French press and filter drip machine), due to both the high power consumption and packaging materials.

With the goal of providing new solutions for the design and development of new, environmentally friendly packages for single-use coffee servings, we present an alternative approach to obtain plastic capsules with high oxygen barrier properties. In particular, coating technology has been selected as a potential tool for the deposition of high-performance, thin layers that may prevent the oxidation of the food matrix. For this purpose, we propose a double-step approach consisting of the following: (i) flame-assisted surface activation of the polymer substrate and (ii) spray-mediated deposition of a hybrid nanostructured oxygen barrier coating.

2. Materials and methods

2.1. Materials

Injection-molded polypropylene (type 30IS, Polychim Industrie, France; nucleated homopolymer with good antistatic properties, melt flow index according to ASTM D1238 = 50 ± 5 g/10 min; density according to ASTM 1505 = 0.9 g/cm^3; surface energy ~ 27 mJ m^{-2}) capsules (volume ~ 16.77 mL; bottom diameter: 29.35 mm; top diameter: 39.8 mm; bottom-to-top height: 22 mm; weight: 2.2 ± 0.05 g; mean thickness: 0.8 mm) (Fig. 1a) were kindly provided by Mitaca S.r.l. (Robecchetto con Induno, Italy).

High-purity tetraethoxysilane (TEOS, Sigma–Aldrich, Milan, Italy) was used as the metal alkoxide precursor of the inorganic phase within the coating formulation, whereas pullulan powder (PF-20 grade, M_n ~ 200 kDa; Hayashibara Biochemical Laboratories Inc., Okayama, Japan) was used as the organic counterpart; 1 M hydrochloric acid (Sigma–Aldrich, Milan, Italy) was used as the catalyst. All materials were used as received for the preparation of the hybrid solution. Ethanol (96% v/v; Sigma–Aldrich, Milan, Italy) and Milli-Q water (18.3 MΩ cm) were used as the only solvents throughout the experiments.

2.2. Methods

2.2.1. Surface modification apparatus and procedures

With the goal of increasing the surface energy of pristine PP capsules, a treatment mediated by a flame was performed with pilot-plant-flaming equipment built within our labs (Fig. 1b). It basically consists of a feeding system (fuel and oxidizer cylinders) connected to a fuel/oxidizer mix generator (mod. EI-080, esseCI srl, Narni, Italy); two single-flow-tube universal rotameters (ASA, Sesto S. Giovanni, Italy), one for the oxidizer (mod. 1901, flow range$_{air}$ 85–850 L h^{-1}, 1013 mbar, 20 °C), one for the fuel (flow range$_{air}$ 4–115 L h^{-1}, 1013 mbar, 20 °C); a pressure gauge; an in-line mixture sampling device; a 100 mm × 20 mm ribbon burner with no-return flame valves (esseCI srl, Narni, Italy); and a sample holder composed of an aluminum rotating cylinder (where the capsule is placed) and a speed-regulating automatic device. Ignition of the flame was accomplished by an electric spark.