

Article

Effects of Aluminium Coated with Stainless Steel on the Nutritional Quality of Tomato Products

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Abstract

This study evaluated the storage stability of tomato juice, paste, and purée packaged in conventional aluminium containers (ACs) and aluminium containers coated with a food-grade stainless steel layer (ASSCs). The objective was to determine whether the stainless steel coating could reduce aluminium ion migration, preserve the physicochemical and nutritional quality of tomato products during storage, and decrease the need for antioxidant, antifungal, and acidifying additives. The stainless steel coating improved the barrier performance of the Al substrate by reducing its porosity from 6.0% to 3.8%. During storage, tomato products in ACs exhibited a marked decrease in acidity (7.65–4.07 g/100 g), whereas samples stored in ASSCs showed a smaller reduction (7.65–5.98 g/100 g), indicating enhanced chemical stability. Increasing NaCl concentrations promoted Al migration, reaching 26.4 mg/kg in AC but only 9.2 mg/kg in ASSC. The vitamin C content remained nearly unchanged (2.09–2.04 mg/100 g), while total polyphenols decreased slightly (110.13–98.81 mg/100 g). Mineral analysis (Al, Cr, Mn, Ni, Zn, Fe, and Ca) confirmed higher metal concentrations in AC-stored samples, whereas aluminium migration was effectively minimised in ASSCs. These findings demonstrate that stainless steel-coated aluminium provides superior corrosion resistance, limits metal transfer, preserves the physicochemical and antioxidant quality of the tomato products, and represents a promising packaging material for extending shelf life while reducing the need for food additives.

Keywords: smart solutions for packaging; food safety; storage in stainless steel-covered containers



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1. Introduction

Many results were obtained from an experiment based on using a Glide-arc type plasma reactor operating at atmospheric pressure to assess the quality of fresh pressed tomato juice, variety Bekas. Significant increases were observed in total soluble solids, pH, lycopene, and vitamin C when Cold Atmospheric Plasma (CAP) was used to treat the tomato juice in comparison to the control treatments. A significant decrease was observed in total plate count, yeast, and mould after 300–600 s of CAP treatment [1].

Most of these juices are pasteurised to eliminate microorganisms present in the products. Elimination of bacteria protects the products against spoilage, thereby extending their storage stability over a long time. However, this treatment process can destroy not only microorganisms, but also many valuable biologically active substances [2,3]. Properties such as pH, Brix, lycopene, and vitamin C were slightly increased by cold plasma treatment.

During storage time, the CAP-treated juice was more stable, while the untreated juice (control) showed gradual changes in physicochemical properties. CAP treatment may better preserve the original colour of the tomato juice, especially after a long storage time, since the samples tested on day 10 were characterised by the lowest absolute value of colour difference (DE).

International research studies show that the presence of salts and catalysts, like sodium chloride and copper ions, in food speeds up the chemical corrosion of aluminium cans or cooking pots [4].

Aluminium is a material used in various sectors, such as packaging of food, cosmetics, pharmaceuticals, household items, and construction, as well as in aircraft manufacturing. Advantages for using it as food packaging are well known and documented, including basic requirements for food preservation such as protection from light and the provision of gas barriers, as well as versatility, post-consumer material recycling, and corrosion resistance. However, when exposed to certain conditions found in food and beverages, such as acid or media containing chlorides, there are some disadvantages [2,4].

Other components normally found in tomato juices, food, and beverages can also induce, catalyse, or strengthen the aluminium packaging corrosion process. The presence of oxidising agents in the product a contributing factor for metal dissolution in food cans, and this class of agents includes substances such as pigments and metallic ions such as iron [2].

Furthermore, the chloride ion is often considered one of the main compounds that begins the localised corrosion process in aluminium alloys [2]. The first step in initiation of the pit corrosion process involves the adsorption of chloride ions onto the oxide layer surface. Aluminium cans for beverages are made of two aluminium alloys. The 3104 alloy is used for the body (one-piece part that comprises the bottom and wall) of the can due to its ductility—a property that allows the draw and wall ironing process to form the can.

The migration of aluminium (Al) ions into liquid food products like tomato juice and beer is determined by their chemical characteristics (acidity, electrolyte content) and storage temperature. This can affect packaging integrity and sensory quality and presents potential health risks [2].

The migration mechanism and the triggering factors are the acidity and pH of tomato juice (which is highly acidic), which attack the natural aluminium oxide layer on the surface of the containers.

The application of the analysed processing technique has many advantages in terms of both the microbiological quality and the nutritional value of products [4–11].

2. Materials and Methods

2.1. Materials

In the present work, only anodised aluminium alloy covered with oxides was used. The protective layer is resistant to corrosion, but it has a porosity of 6% that allows microorganisms to penetrate the surface layer of the alloy.

Technologically, this problem is solved by washing with caustic soda, which carries food safety risks through chemical contamination.

By covering the aluminium alloy with a layer of stainless steel, the porosity of the aluminium alloy decreases from 6% to 3.8%, which has been experimentally demonstrated, and washing the containers is done by automatic CIP (Cleaning in Place) programs. The method today offers the best results by applying sanitation tests.

In order to carry out our own research, aluminium alloy samples—EN AW 2007 with dimensions 120 mm × 180 mm × 15 mm—were covered by thermal spraying in an electric arc, with layers of food grade stainless steel wire, type 80T, made by Tafa-Praxair Co. USA

(Indianapolis, IN, USA)—according to Toma et al. [12]. In total, 64 samples were coated. Table 1 presents the commercial chemical composition of the substrate and of the material that was used [13].

Table 1. Chemical composition of the materials.

Materials	Chemical Composition (wt.%)										
	C	Cr	Mn	Ni	Si	Ti	Cu	Mg	Al	Zn	Fe
80T	0.12	18	1.5	0.5	-	-	-	-	-	-	Balance
ENAW 2007	-	0.1	0.8	0.1	0.8	0.2	3.7	0.8	Balance	0.8	-

2.2. Applying the Coating

Before being coated, the steel samples were cleaned by sandblasting with corundum of a grain size of EKF 14, at pressure $p = 3.2$ bar, and then they were chemically cleaned by washing with ethanol in order to eliminate traces of fats. The operation was necessary to ensure the minimum roughness of $R_a = 11.5 \mu\text{m}$ necessary to obtain high adhesion [11–16]. Table 2 presents the process parameters used to cover the aluminium samples with a layer of stainless steel [17,18].

Table 2. Technological parameters.

Parameter	Value
Current intensity (A)	220
Voltage (U)	32
Primary air pressure (bar)	6
Movement speed of the gun (m/s)	0.14
Stand-off distance—SOD (mm)	100
Number of passes	3

2.3. Coating Characterisation

It is known that the existence of a layer with reduced porosity and high adhesion determines perfect sealing of the substrate [19]. To confirm this, the obtained deposits were microstructurally characterised, the degree of porosity, adhesion was evaluated, and the microhardness was determined.

The microstructural and chemical characterisation of the deposits was carried out with the help of an electronic SEM scanning microscope, type Vega II LSH (Tescan—Kohoutovice, The Czech Republic), equipped with an EDAX spectroscope in order to determine the chemical composition. Thus, after being sliced on the transverse plane and mounted in conductive resin, ground, and then polished on the cross section, in compliance with standard metallographic procedures, the samples were investigated on the cross section using SEM.

The IQ materials image analysis software program (manufactured by Media Cybernetics—Rockville, MD, USA) was used to evaluate the porosity of the deposits. Thus, by analysing the micro-graphs with an area of approx. 0.1 mm^2 , taken using a bright field, at $300\times$ magnification, on an optical microscope Optika SZM 2 made by Optika (Via Rigla, Ponteranica (BG), Italy), the porosity of the coated layer was evaluated.

After microscopic examination and porosity determination, the same samples were used to determine Vickers microhardness using a CV-400DAT digital microhardness meter produced by CV Instruments (Sheffield, UK). The tests were carried out under loads of 300 gf, using a penetration time of 15 s, for a total of 15 measurements [18].

Adhesion of the deposited layer to the substrate was assessed by tensile testing, in accordance with the European norm EN 582 ([SR ISO 750/2008]), on five samples with dimensions of 40 mm × 40 mm × 15 mm [17].

2.4. Determination of the Acidity of the Samples

Testing of the acidity of the samples. In a titration glass, 10 mL of tomato products was homogenised with 20 mL of distilled water (with the same pipette), and a few drops of phenolphthalein are introduced. The contents of the glass were homogenised and titrated with NaOH 0.1 n until the appearance of pale pink coloration that persisted for 30 s. The acidity was calculated according to the formula $^{\circ}\text{A} = V1 \times 100/V2$, where $V1$ = mL NaOH 0.1 n used in titration, and $V2$ = mL sample used in the analysis [18].

2.5. Determination of pH Index

The pH was measured using a TESTO 205 pH meter (Testo SE & Co. KGaA: Lenzkirch, Germany), after calibrating the measuring instrument with the solutions from the device kit. The calibration was performed by placing the pH meter probe in the calibration solutions when the device showed the reference values at 20 °C. Then, the pH measurements for the tomato samples were taken by placing the device's probe in the lab samples at a temperature of 20 °C.

2.6. Determination of Ascorbic and Dehydroascorbic Acid Contents by HPLC

Samples preparation. First, 5 g of sample was mixed with 50 mL of aqueous metaphosphoric acid solution for 1 min in a blender. The homogenised sample was centrifuged at 4000 rpm for 20 min. Then, it was filtered with a 0.45 µm microfilter under vacuum, and the filtrate was injected into the HPLC column. At minute 0, a peak appeared, which showed the level/concentration of ascorbic acid, and it decreased over 30 min. For the HPLC analysis of ascorbic and dehydroascorbic acid, a 3% or 5% (*w/v*) metaphosphoric acid solution was used for extraction, within an RP-HPLC (reverse phase) system equipped with a C18 column. The standard method was used, according to the optimisation data, which involved a mobile phase flow rate of 1.0 mL/min and three parallel injections (triplicate), at a wavelength of 243–265 nm. In the case of the dehydroascorbic acid, the extinction coefficients were detected at a wavelength of 185–220 nm.

2.7. Determination of Total Polyphenol Content

The experimental protocol (standard method) was as follows. Initial mixture: pipette exactly 0.5 mL of sample extract or gallic acid standard into a test tube. Adding the acid reagent: add 2.5 mL of Folin–Ciocalteu reagent (pre-diluted 1:10). First incubation: mix well and let the mixture sit for 3–5 min at room temperature. This step allows the reagent to interact with polyphenols in an acidic environment before neutralisation. Alkalinisation (creating the reaction environment): add exactly 2.0 mL of 7.5% sodium carbonate solution. The role of the carbonate is to alkalinise the medium, the only way the blue molybdenum-tungsten complex can form. Bringing to volume (optional, depending on the kit): top up with distilled water to a total volume of 5 mL. Final incubation (colour development): the tubes are mixed and incubated in the dark for 30 min at 40 °C in a water bath. Spectrophotometric measurement: the absorbance of the samples is read at a wavelength of 765 nm–760 nm against a blank sample in which the extract was replaced with extraction solvent [20].

2.8. Determination of Soluble Dry Matter Content

The refractometric method is based on measuring the refractive index of the analysed solution at a standard temperature of 20 °C. The angle at which a light beam is refracted

(changes direction) when passing through the liquid sample is directly proportional to the concentration of dissolved solid compounds. The results, read on the scale of the Abbe refractometer or digital refractometer, are expressed directly in degrees Brix ($^{\circ}\text{Bx}$), where $^{\circ}\text{Bx}$ is equivalent to 1 g of sucrose per 100 g of solution.

Equipment and materials: a refractometer (equipped with Automatic Temperature Compensation—ATC, or a conventional Abbe refractometer) was used. Distilled water was used for calibration and for setting the instrument's zero point. The obtained tomato samples (S1, S2, S3) were then placed individually on the refractometer prism. Three readings were taken for each sample, and the final result represents the arithmetic mean of the measurements obtained experimentally [18].

2.9. Multi-Element Analysis by ICP-MS

Multi-element determination was performed using an Agilent 7700 ICP-MS instrument (Santa Clara, CA, USA). To optimise detection of the analytes of interest, the collision/reaction cell was operated in both “He mode” and “no-gas mode.” For the ICP-MS analysis, the mass-to-charge ratios (m/z) were monitored and recorded for Al, Cr, Mn, Ni, Zn, Fe, and Ca.

This approach was used as an internal standard to compensate for instrumental drift. To evaluate method accuracy via recovery matrix tests, two spiked tomato samples were prepared with the selected elements Al, Mn, Fe, Ca, Cr, and Zn. The ICP-MS system and its associated accessories were fully automated and computer-controlled using the Agilent Mass Hunter software (G7201A Workstation versions A.01.02) suite [21,22].

2.10. Determination of Transmittance Levels in Tomato-Based Products

The samples were analysed for transmittance values at wavelengths within the range of 234–265 nm using a UV–VIS spectrophotometer (Vortex VIS Spectrophotometer, Munich, Germany). This analysis was performed in accordance with the studies conducted by Kumar and Viswanathan [22] and Orozco et al. [23].

3. Results and Discussion

3.1. Results for Porosity and Adhesion

Figure 1 presents the SEM micrograph of the cross-section of food grade stainless steel layers deposited by thermal spraying in an electric arc on an aluminium alloy support. The lamellar structure of the layer, which presents flattened particles, pores, communication channels between pores, and non-melted particles, is a typical structure of coatings obtained by thermal spraying in an electric arc. The different brightness values, as well as the predominantly light grey shades, also indicate almost complete mixing of the various alloying components [21].

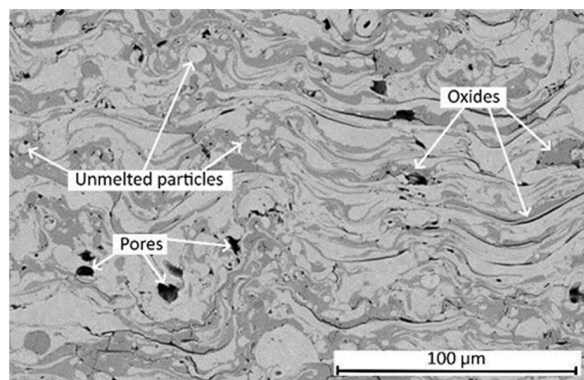


Figure 1. SEM micrograph of a cross-section of the 80T coating [19].

The average values of porosity and adhesion obtained after performing the specific tests are presented. The obtained values are in accordance with the results obtained by other researchers in the field [19].

The high value of the average adhesion, as well as the low value of the porosity, of the layer allow its use for the purpose of protecting aluminium surfaces. (see Table 3).

Table 3. Average values of adhesion, porosity, and hardness of 80T deposits [19].

Coating	Adhesion, [MPa]	Porosity, [%]	HV ₃₀₀
80T	32.7	3.8	308 ± 25

The high value of the microhardness of the deposit is due to the presence of chromium in the wire used (18%Cr—see Table 1), a fact that determines the formation of complex carbides of chromium, known as constituents with high relative hardness [21].

3.2. Results for the Tomato Samples

The research experiment investigated the nutritional qualities of the tomato products by measuring components like ascorbic acid (vitamin C), polyphenols, dry substance matter, and transmittance level during contact with aluminium (Al) ACs, as well as with stainless steel-coated ASSCs. Determinations were carried out for the soluble dry matter content, ascorbic acid concentration, polyphenol content, acidity, and pH index of tomato juice S1, tomato paste S2, and tomato purée S3. The tomato samples were taken from the Tecuci canning factory.

The experimental study did not focus on the behaviour of the samples in glass packaging, but on storing the tomato samples in containers along the production line until final packaging. That is why there was no analysis of samples in control glass packaging. The tomato samples were analysed under storage conditions of 2–8 °C, 75–80% relative humidity, and natural light over a period of 3 to 12 months.

The tomato samples used in the experiment—namely S1 (tomato juice with 1.5% NaCl), S2 (tomato paste with 2.5% NaCl), and S3 (tomato puree with 3.5% NaCl)—had medium soluble dry matter contents of 8%, 12%, and 24%, respectively, at 12 months. Statistical analysis of the experimental data revealed a strong linear trend for samples stored in aluminium containers (ACs), demonstrating a good fit with a coefficient of determination of $R^2 = 0.9167$. An equally positive and significant linear correlation was observed for samples stored in stainless steel-coated aluminium containers (ASSCs), yielding an R^2 value of 0.9412 after 12 months. See Figure 2.

The average values of soluble dry matter content after 12 months are similar to the initial values because the porosity of the ASSCs was very low, below 3.8% [19] (see Table 3), and the moisture of the tomato products remained constant. The linear statistical regression curves overlap. See Figure 2.

The decrease in acidity of the tomato samples stored in ACs from 7.65 g/100 g to 4.07 g/100 g (See Figure 3a) shows that acidity causes the migration of Al ions. When storing the samples in ASSCs, the acidity varied moderately from 7.65 g/100 g to 5.98 g/100 g, which leads to better results when the aluminium is coated with a stainless steel layer. See Figure 3b.

Variation of the pH index from 4.3 to 3.5 suggests that, when storing tomato samples in ACs, there is a risk of alcoholic and acetic fermentation, which is also indicated by a pH of 3.5. See Figure 4a.

In the case of storing tomato samples in ASSCs, it is observed that the pH index varies between 4.3 and 4.1, which ensures a slightly acidic environment that does not favour

fermentation. Therefore, storing tomato products in aluminium containers covered with stainless steel (ASSCs) could inhibit the development of yeasts, acetic bacteria, and moulds. See Figure 4b.

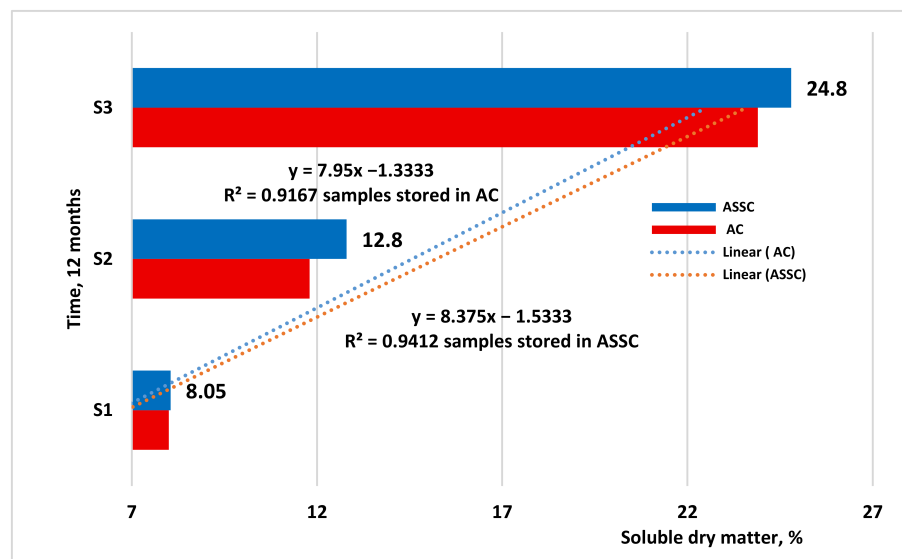


Figure 2. Evolution of soluble dry matter content in the tomato samples S1, S2, and S3 stored in aluminium containers (ACs) compared to those stored in stainless steel-coated aluminium containers (ASSCs) for 12 months.

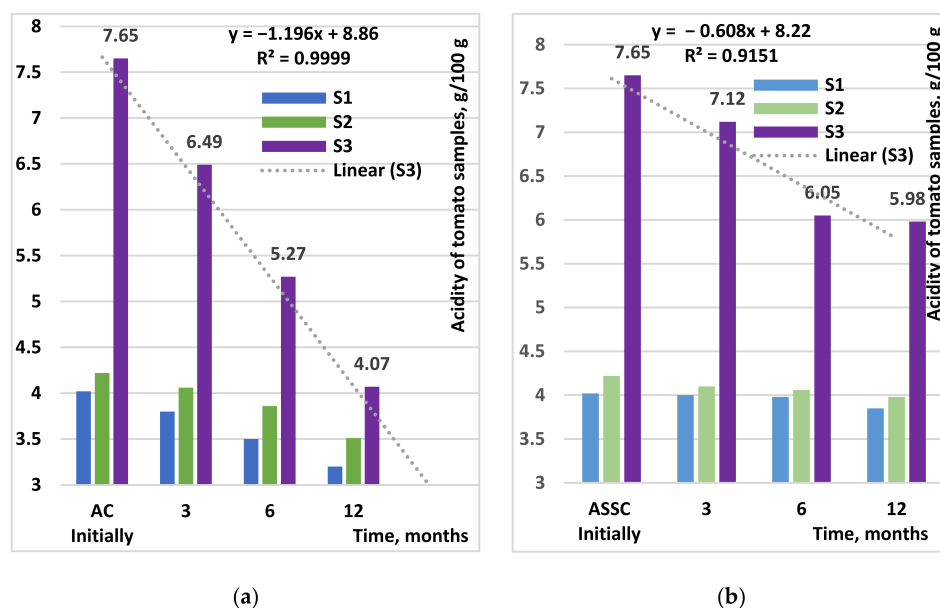


Figure 3. The evolution of acidity in tomato samples S1, S2, and S3: (a) stored in ACs; (b) stored in ASSCs.

The concentrations of ascorbic acid and dehydroascorbic acid in S1-tomato juice, S2-tomato paste, and S3-tomato purée were determined using the HPLC method. The optimal detection wavelengths were 243–265 nm for ascorbic acid and 185–220 nm for dehydroascorbic acid. These concentration variations indicate that the transformation of tomato juice into paste and purée through thermal concentration was successfully achieved, subsequently enhancing the nutritional density of the final products.

The dynamics of ascorbic acid concentration in the tested samples (S1, S2, S3) indicated a decrease in ascorbic acid (vitamin C) content, which consequently decreased the acidity of the medium. See Figure 5. Among the three samples, tomato purée (S3) exhibited the

highest risk of sensory, physicochemical, and microbiological deterioration. In this sample, the variation in ascorbic acid concentration from 2.7 mg/100 g to 2.09 mg/100 g resulted in a significantly more acidic environment, creating favourable conditions for spoilage through the proliferation of mould spores and acetic acid bacteria, leading to both mould growth and acetic fermentation. The development of mould and acetic bacteria can cause tomato samples to spoil, and this is also promoted by the acidic pH of 3.2 in ACs. Combined with changes in ascorbic acid, this favours the spoilage of tomato samples stored in ACs. See Figure 5a.

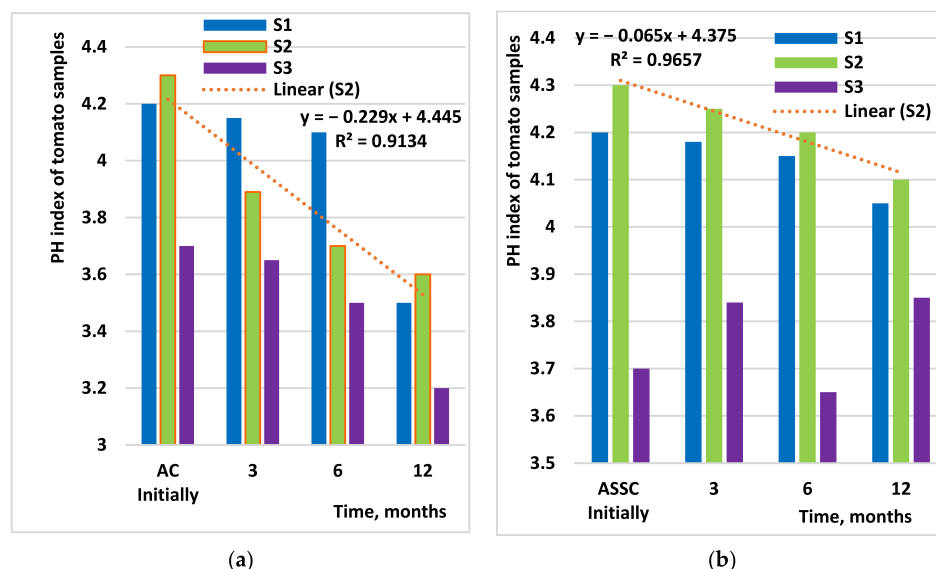


Figure 4. Variation in the pH indices of tomato samples S1, S2, and S3: (a) stored in ACs; (b) stored in ASSCs.

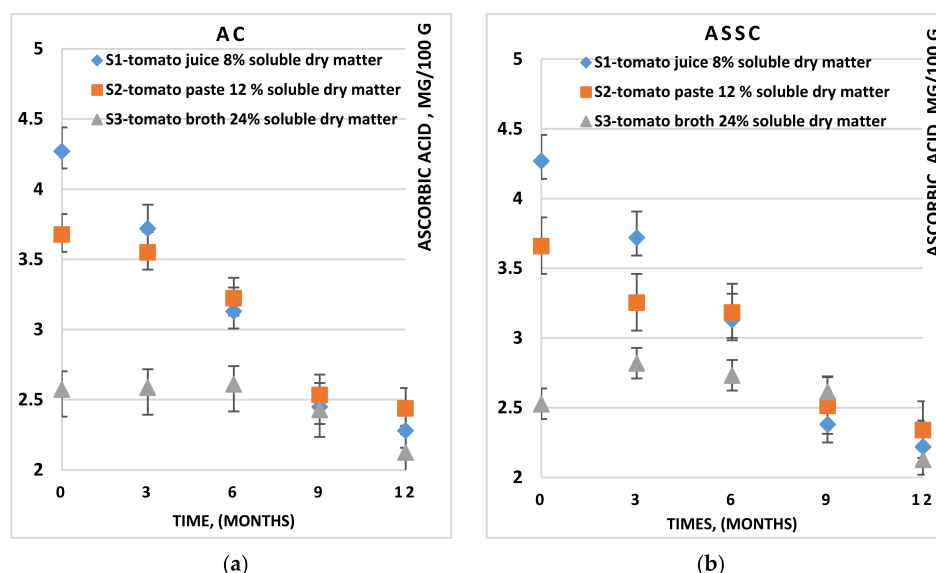


Figure 5. Dynamics of ascorbic acid content in tomato samples: (a) stored in ACs for 12 months; (b) stored in ASSCs for 12 months.

In contrast, when stainless steel-coated aluminium containers (ASSCs) were used, the risk of sensory changes and subsequent deterioration was reduced. The minor variation in ascorbic acid concentration from 2.09 mg/100 g to 2.04 mg/100 g maintained a stable acidic environment, thereby significantly reducing the spoilage risks identified previously. See Figure 5b.

The oxidation of tomato juice S1, tomato paste S2, and tomato purée S3 resulting from contact with solubilised aluminium ions also induces an unpleasant metallic taste. The solubilisation of Al ions in tomato juice and tomato paste, in the presence of oxygen and at elevated temperatures, promotes the oxidation of ascorbic acid (vitamin C), thereby reducing the ascorbic acid content of these tomato products. See Figure 5a. By using the ASSC method, the ascorbic acid level of 2.04 mg/100 g allows maintenance of a slightly acidic, fresh taste, thus preventing the oxidation of tomato products. See Figure 5b.

The total polyphenol concentration in samples S1, S2, and S3 stored in stainless steel-coated aluminium containers (ASSCs) exhibited greater stability, ranging from 110.13 mg/100 g to 98.81 mg/100 g.

This retention represents a significant advantage for preserving and enhancing the nutritional characteristics of tomato-based products. See Figure 6b. Therefore, the use of stainless steel-coated aluminium containers (ASSCs) represents an excellent solution for food preservation, effectively preventing the degradation of polyphenol contents (Figure 6a). A higher content of polyphenols is associated with enhanced antioxidant properties.

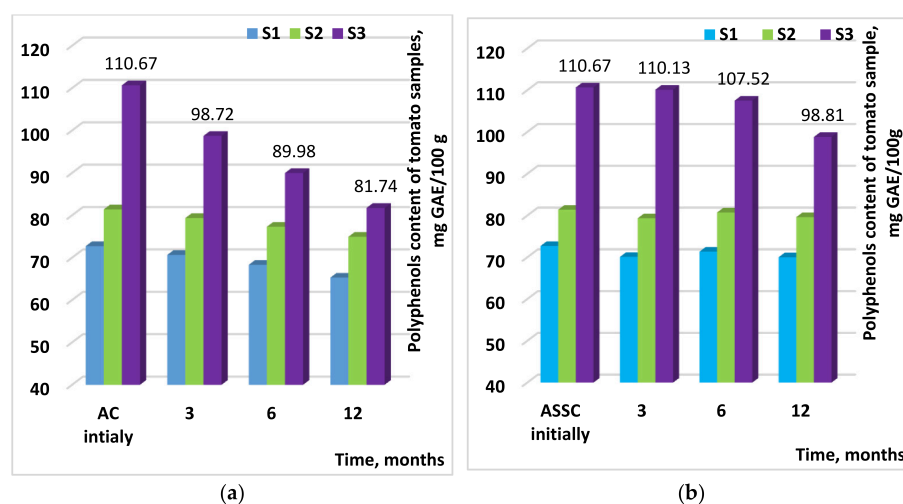


Figure 6. Dynamics of total polyphenol content in tomato samples stored in (a) ACs and (b) ASSCs for 12 months.

Consequently, the natural colour of S1-tomato juice, S2-tomato paste, and S3-tomato purée can be preserved by maintaining a high polyphenol content. In contrast, comparative analysis of samples stored exclusively in uncoated aluminium containers (ACs) indicated a significant decrease in the total polyphenol content. See Figure 6a.

Furthermore, dissolved aluminium ions interact with polyphenols, triggering their oxidation and altering the colour of samples S1, S2, and S3. Due to the compounds formed during this oxidative process, the colour changes to an undesirable brownish shade. See Figure 6a.

Therefore, the transmittance of tomato products S1, S2, and S3 in contact with uncoated aluminium (AC) was analysed and compared with the transmittance values determined for stainless steel-coated aluminium (ASSC) material. See Figure 6b.

From a nutritional point of view, the total polyphenol content in tomato-based products has also been studied, and this decreases in the presence of oxygen, which also indirectly promotes the migration of Al ions.

As a result of the fact that modern human nutrition recommends consuming foods that contain high levels of antioxidant substances like ascorbic acid and polyphenols, the research experiment shows that covering the Al material with a stainless steel layer makes the experimentally determined antioxidant substances—ascorbic/dehydroascorbic

acid, polyphenols—from samples S1, S2, and S3 to decrease less during storage over 6 or 12 months, which ensures a higher antioxidant content in ASSCs compared to ACs. See Figures 5a,b and 6a,b.

Modern medical and nutrition studies showed that polyphenols have an antioxidant effect and act by reducing free radicals formed during metabolism.

Polyphenols are bioactive compounds that act as antioxidants, neutralising free radicals and preventing oxidative stress. By donating an electron or a hydrogen atom, polyphenols stabilise these unstable molecules before they can damage cells, proteins, or DNA. They protect the body against chronic diseases and premature aging.

Polyphenols take the unpaired electrons from free radicals, turning them into stable and harmless molecules. In addition to their antioxidant effect, polyphenols also modulate inflammatory pathways in the body and reduce the production of cytokines associated with chronic diseases.

Polyphenols thus support the immune system along with vitamin C (ascorbic/dehydroascorbic acid). These compounds support the body's own antioxidant systems and help repair existing cellular damage [24].

Although polyphenols and vitamin C (ascorbic/dehydroascorbic acid) are very important substances from a nutritional point of view, they are not standardised in the scientific literature for reasons that are scientifically and technologically justified and rely on soil and climate conditions.

In this context, the content of vitamin C and polyphenols is very variable in tomatoes because, from a pedoclimatic point of view, the formation of nutrients in tomato crops depends each production year on the level of rainfall and the number of sunny days, which, by stimulating photosynthesis and the biodegradation of reserve substances in the soil, promote the transformation and storage of organic substances in plants, specifically the accumulation of ascorbic acid or polyphenols in tomato fruits [24,25].

These are the most important advantages of foods from a nutritional standpoint, contributing to better overall health for the population. So, the research experiment aimed to test the content of polyphenols during the storage of tomato products S1, S2, and S3 over a 12 month period, both in contact with ACs and in contact with ASSCs.

The results showed that the total polyphenol content (98.81 mg GAE/100 g) in ASSCs is much higher than that in ACs (81.74 mg GAE/100 g).

Otherwise, not protecting containers (ACs) with protective coatings, such as stainless steel coatings, leads to effects that will degrade the quality of tomato juice, paste, or puree due to the high acidity from citric acid, malic acid, ascorbic acid, dehydroascorbic acid, and acetic acid resulted from accidental acetic fermentation, which aggressively interacts with unprotected aluminium.

This affects the corrosion process and causes an unpleasant metallic taste in tomato products.

Experimental research studies have shown that storing tomato juice in aluminium containers, especially in cans with cracked protective coatings or in non-anodised containers, dramatically increases the concentration of soluble Al [26].

From Table 4, it is observed that $p \leq 0.05$, and the difference is considered significant.

Table 4. ANOVA analysis regarding the polyphenol contents of S1, S2, and S3 in the case of storage in ACs/ASSCs.

Source of Variation	SS	df	MS	F	<i>p</i> -Value	F Crit
Total polyphenol content in ACs	1571.18548	2	785.59274	31.69786656	0.0001576	4.4589701
Total polyphenol content ASSCs	373.9403333	4	93.48508333	3.872027854	0.0500949	3.8378534

Two-factor ANOVA with replication.

The calibration curve of the spectrophotometer showed a transmittance range between 89.99% and 99.1%. See Figure 7.

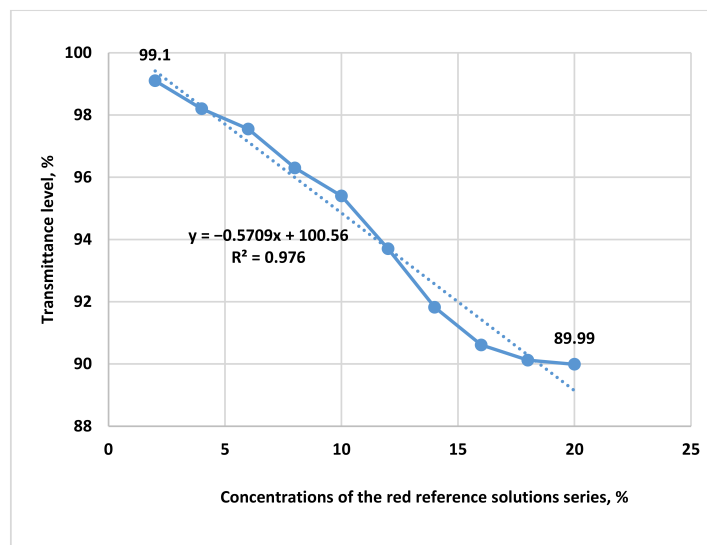


Figure 7. Transmittance of the standard series of red reference solutions.

Consequently, the transmittance of tomato samples S1, S2, and S3 in contact with uncoated aluminium ACs was analysed and compared to the transmittance values determined for tomato samples stored in stainless steel-coated aluminium ASSCs.

For tomato products stored in aluminium containers (ACs), transmittance decreased from the initial values of 7.2% (S1-tomato juice), 18.4% (S2-tomato paste), and 36.1% (S3-tomato puree) to 5.42%, 11.27%, and 16.38%, respectively, after 12 months of storage. See Figure 8a. In contrast, when S1, S2, and S3 were stored in stainless steel-coated aluminium containers (ASSCs), transmittance remained more stable; the recorded variation was significantly smaller, changing only from 35.98% to 35.41%. The level of transmittance in this case was more than 16.83% for S3 tomato puree. See Figure 8b. The linear regressions recorded for the experimental values are above average. See Figure 8a,b.

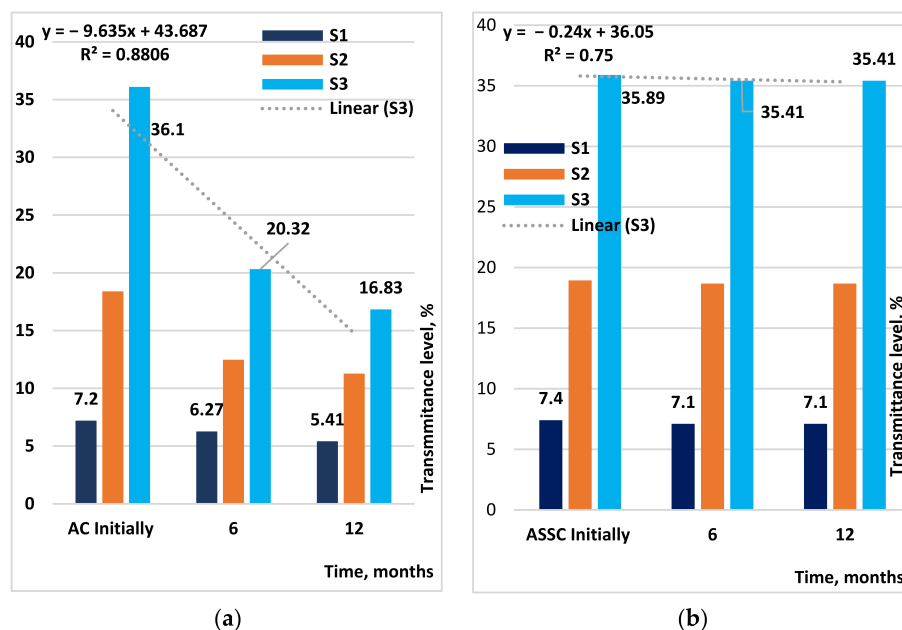


Figure 8. Transmittance values of tomato samples after 6 to 12 months of storage in (a) aluminium containers (ACs) and (b) stainless steel-coated aluminium containers (ASSCs).

3.3. Results for Selected Metals Present in the Tested Tomato Samples

The NaCl concentration in the damaged tomato samples, from 1.5% to 3.5%, significantly affected the migration of Al ions and other metals into the tomato paste and tomato puree. See Table 5 for the results from grinding samples stored in uncoated aluminium containers (ACs). There is a noticeable increase in the Al concentration from 0.87 mg/kg in tomato juice with 1.5% NaCl to 26.4 mg/kg in tomato puree that had 3.5% NaCl. This experimentally showed the accelerated migration of Al ions when the NaCl concentration is more than double in tomato sample S3.

Table 5. Recovery percentage for selected metals in dilutions of the tomato samples without additives stored in ACs for 12 months at 2–8 °C.

Measured Concentration of Metals, mg/kg	Al	Cr	Mn	Ni	Zn	Fe	Ca
Standard concentration of metals, max.mg/kg	5	1.85	0.45	0.1	0.01	1.2	150
S1-tomato juice 1.5% NaCl	0.87	0.38	0.771	0.081	1.12	0.7	15.7
Deviation	±4.13	±1.47	−0.321	±0.019	−1.11	±0.5	±134.3
S2-tomato paste 2.5% NaCl	11.26	0.378	3.45	0.37	1.25	0.92	20.1
Deviation	±6.26	±0.228	±3.47	±6.55	±23.75	±14.08	±29.9
S3-tomato puree 3.5%NaCl	26.14	0.89	4.89	0.84	2.3	0.98	25.5
Deviation	−5.14	±1.61	±1.08	±6.08	±22.7	±49.02	±334.5

In the case of the tomato samples stored in ASSCs, the increase in Al concentration from 0.5 g/kg in sample S1 with 1.5% NaCl to 9.2 mg/kg in sample S3 with 3.5% NaCl is justified only by the concentration of the tomato paste, as the soluble dry matter increased from 8% in sample S1 to 24% in sample S3 through multi-step concentration of the tomato juice.

In this case, storing the tomato samples S1—1.5%, S2—2.5%, and S3—3.5% NaCl in ASSCs, the maximum NaCl level of 3.5% no longer affects the migration of Al ions (Table 6).

Table 6. Recovery percentage for selected metals in diluted tomato samples without additives stored in ASSCs for 12 months at 2–8 °C.

Measured Concentration Metals Al, mg/kg	Al	Cr	Mn	Ni	Zn	Fe	Ca
Standard concentration of metals Al, max.mg/kg	3	1.8	0.5	0.01	5	2	150
S1-tomato juice 1.5% NaCl	0.5	0.3	0.515	0.08	1.12	0.65	15.65
Deviation	±2.5	±1.5	−0.015	−0.07	±3.88	±1.35	±134.35
S2-tomato pasts 2.5% NaCl	9.04	0.14	2	0.22	1.25	0.9	19.95
Deviation	±0.96	−0.11	±0.33	−0.12	−0.75	±69.1	±160.05
S3-tomato puree 3.5% NaCl	9.2	0.34	3	0.27	2.2	0.92	25.45
Deviation	±0.8	−0.24	−1	−0.17	−1.5	±19.08	±324.55

It can be seen that the tomato samples stored in ASSCs had much lower aluminium concentration values compared to the tomato products stored in ACs.

From Table 7 it can be observed that $p < 0.05$. The difference is considered significant.

Table 7. ANOVA regarding the mineral contents of S1, S2, and S3 stored in ACs/ASSCs.

Source of Variation	SS	SSS	SS	df	MS	F	p-Value	F Crit
Tomato samples	22970263			28	820,366.5	1.000081	0.045998	1.576943
Mineral content	27427114			4	6.856,778	8.358869	6.15×10^{-6}	2.452716

Two-factor ANOVA with replication.

4. Conclusions

This experimental study demonstrated that, coating the surface of aluminium with a layer of food-grade stainless steel deposited by electric arc thermal spraying, represents an effective solution for the development of functional materials intended for contact with food products, like tomato products. The primary role of the coating was to act as a protective barrier against oxygen permeability and the migration of metallic ions from the aluminium substrate into the food medium.

Structural characterisation of the stainless steel coatings revealed the formation of compact layers with low porosity and high adhesion to the substrate. These characteristics directly contributed to improving the sealing capacity of food containers and to limiting oxidative processes occurring during storage. These are combined with the presence of polyphenols and ascorbic acid in tomato products, which have the same antioxidant effect.

In the case of tomato-based products, aluminium containers coated with a stainless steel layer reduced the oxidative degradation of ascorbic acid and polyphenolic compounds, maintaining the colour stability and antioxidant properties of the products throughout the storage period.

In conclusion, this study addresses experimental limitations by examining nutritional quality indicators—specifically acidity, pH, and ion migration in the presence of NaCl. The reduction in food additives is justified by the results regarding ascorbic acid and polyphenol content, as well as acidity and pH levels, monitored over a storage period of up to 12 months. Currently, tomato products are preserved for 24 to 36 months through the addition of preservatives, antifungals, and antioxidants. The presence of ascorbic acid and polyphenols protects tomato products against oxidation without the need for added antioxidant additives. Reducing container porosity—from 6% in ACs to 3.8% in ASSCs—favourably influences the preservation of tomato products by inhibiting moulds that thrive in the presence of oxygen, eliminating the need for exogenous antifungal additives.

Compared with conventional aluminium containers (ACs), the ASSC system exhibited significantly smaller variations in ascorbic acid and polyphenol concentrations, demonstrating the effectiveness of the coating layer as a functional barrier against oxidation.

Other negative aspects like fermentation, and consequently spoilage, can be avoided by controlling acidity and pH at the recommended refrigeration temperatures.

The reduction of interactions between the acidic food medium and the aluminium substrate limited the solubilisation of aluminium (Al) ions and associated oxidation processes, preventing undesirable sensory changes such as metallic taste and product browning. The superior stability of optical transmittance observed in samples stored in ASSCs confirms the effectiveness of the coating in preserving the visual and nutritional properties of food products.

Accidental increases in temperature above 2–8 °C, as well as the presence of some non-compliant spoilage microorganisms in the product mass, could also affect storage in ASSCs. However, these aspects are not related to the aluminium being coated with a stainless steel layer.

From a surface engineering perspective, the results confirm that stainless steel deposits produced by electric arc thermal spraying can be used as functional coatings for advanced food-contact materials, capable of improving product stability, reducing oxidation processes, and extending the shelf life of food products.

Future research should focus on investigating the mechanisms of oxygen diffusion through the coating, evaluating its corrosion behaviour in complex food media, and optimising the microstructure of the coatings in order to enhance their barrier performance and long-term durability in service.

The main limitation of this study is that only one coating system produced by electric arc thermal spraying on the aluminium substrate was evaluated.

Although the results confirm the protective role of the stainless steel coating in reducing aluminium migration and preserving products stability, the long-term behaviour of the coating under real industrial conditions, including repeated cleaning cycles, thermal exposure, and contact with different food media, requires further investigation.

We could also simulate other usage limits for aluminium containers coated with a stainless steel layer, in the case of high concentrations of acetic acid or high concentrations of NaCl, which can cause pitting. However, it has been shown that tomato samples have a pH index of 3.0–4.7, which does not indicate a corrosion risk in any situation.

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