INFLUENCE OF FATLIQUOR CHEMISTRY ON FOGGING AND ODOUR CHARACTERISTICS OF AUTOMOTIVE LEATHER: A COMPARATIVE STUDY OF COMMERCIAL FATLIQUORS

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ABSTRACT. Fogging and odour emissions are among the most important quality requirements for automotive leather due to their direct impact on passenger comfort, interior air quality and driving safety. Fatliquors are indispensable components in leather manufacture, providing softness, flexibility, fullness and durability; however, they are also recognized as one of the major sources of volatile substances responsible for fogging and odour formation. Therefore, the selection of appropriate fatliquor systems is critical for the production of automotive leathers with low emission characteristics. In this study, commercially available fatliquors supplied by three different suppliers with different chemical compositions, including phosphoester-based, fish-oil-based, ester-based, lecithin-containing and synthetic formulations were comparatively evaluated. Automotive leathers prepared with these fatliquors were characterized in terms of fogging behaviour according to DIN EN ISO 17071 and odour performance according to the VDA 270 method. In addition, the effects of fatliquor chemistry on the physical performance of leather were assessed through tensile strength, tear strength and colour fastness with accelerated ageing analysis. The results revealed substantial differences among the evaluated fatliquors in terms of fogging and odour performance. Gravimetric fogging values ranged from 6.8 to 20.8 mg, with synthetic oil, phosphoester and lecithin-based fatliquors generally showing relatively lower fogging tendencies, whereas certain fish oil and ester-based formulations exhibited comparatively higher fogging values. Odour ratings varied between 3.0 and 4.5, and no direct relationship was observed between fogging and odour performance. Notably, considerable differences were also observed among commercial products belonging to the same chemical class, indicating that formulation-specific characteristics play an important role in emission behaviour. These findings demonstrate that fatliquor chemistry and formulation characteristics should be carefully considered when selecting low-emission fatliquors for automotive leather.

KEYWORDS: automotive leather, fatliquor, fogging, odour emission, strength

INFLUENȚA COMPOZIȚIEI CHIMICE A AGENȚILOR DE UNGERE ASUPRA CARACTERISTICILOR DE CONDENSARE ȘI CELE OLFACTIVE ALE PIELII PENTRU TAPIȚERIE AUTO: UN STUDIU COMPARATIV AL AGENȚILOR DE UNGERE COMERCIALI

REZUMAT. Caracteristicile privind condensarea și cele olfactive se numără printre cele mai importante cerințe de calitate pentru pielea utilizată în industria auto, datorită impactului direct al acestora asupra confortului pasagerilor, calității aerului din habitaclu și siguranței la volan. Agenții de ungere sunt elemente indispensabile în fabricarea pielii, conferindu-i acesteia moliciune, flexibilitate, plinătate și durabilitate; cu toate acestea, sunt recunoscuți și ca fiind una dintre principalele surse de substanțe volatile responsabile pentru formarea de condens și a mirosurilor. Prin urmare, alegerea unor sisteme adecvate de ungere este esențială în vederea obținerii pieilor pentru tapițerie auto cu emisii reduse. În cadrul acestui studiu, au fost evaluate comparativ diverse produse comerciale de ungere provenind de la trei furnizori diferiți și având compoziții chimice variate – inclusiv formulări pe bază de fosfoesteri, ulei de pește, esteri, lecitină și produse sintetice. Pielea pentru tapițerie auto prelucrată cu acești agenți a fost caracterizată din punctul de vedere al formării de condens (conform standardului DIN EN ISO 17071) și olfactiv (conform metodei VDA 270). De asemenea, a fost evaluată influența compoziției chimice a agenților de ungere asupra proprietăților fizice ale pielii, analizându-se rezistența la rupere, rezistența la sfâșiere și rezistența culorii în condiții de îmbătrânire accelerată. Rezultatele au evidențiat diferențe semnificative între agenții de ungere evaluați în ceea ce privește performanța legată de formarea de condens și miros. Valorile gravimetrice pentru formarea de condens au variat între 6,8 și 20,8 mg; în general, agenții sintetici, cei pe bază de fosfoesteri și cei cu conținut de lecitină au prezentat tendințe de a forma condens relativ mai scăzute, în timp ce anumite formule pe bază de ulei de pește și esteri au înregistrat valori comparativ mai ridicate. Notele acordate pentru miros au variat între 3,0 și 4,5, neobservându-se o corelație directă între performanța privind caracteristicile de condensare și cele olfactive. Este de remarcat faptul că s-au observat diferențe considerabile chiar și între produsele comerciale aparținând aceleiași clase chimice, ceea ce indică faptul că proprietățile specifice ale formulei joacă un rol important în ceea ce privește emisiile. Aceste rezultate demonstrează că, la alegerea agenților de ungere cu emisii reduse pentru pielea destinată tapițeriei auto, trebuie luate în considerare cu atenție compoziția chimică și caracteristicile formulei.

CUVINTE-CHEIE: piele pentru tapițerie auto, agent de ungere, formare de condens, miros, rezistență

INFLUENCE DE LA COMPOSITION CHIMIQUE DES PRODUITS DE NOURRISSAGE SUR LES CARACTÉRISTIQUES DE CONDENSATION ET OLFACTIVES DES CUIRS AUTOMOBILES : UNE ÉTUDE COMPARATIVE DE PRODUITS COMMERCIAUX

RÉSUMÉ. Les caractéristiques de condensation et olfactives figurent parmi les exigences de qualité les plus importantes pour les cuirs automobiles, en raison de leur impact direct sur le confort des passagers, la qualité de l'air intérieur et la sécurité de conduite. Les produits de nourrissage sont des composants indispensables à la fabrication du cuir, car ils lui confèrent douceur, souplesse, plénitude et durabilité ; toutefois, ils sont également reconnus comme l'une des principales sources de substances volatiles responsables de la formation de condensation et d'odeurs. Par conséquent, le choix de systèmes de nourrissage appropriés est crucial pour produire des cuirs automobiles à faibles émissions. Dans cette étude, des produits de nourrissage disponibles dans le commerce, fournis par trois entreprises différentes et

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présentant des compositions chimiques variées — notamment des formulations à base de phosphoesters, d'huile de poisson, d'esters, de lécithine et de produits synthétiques — ont été évalués comparativement. Les cuirs automobiles traités avec ces produits ont été caractérisés en termes de comportement au condensation (selon la norme DIN EN ISO 17071) et de performance olfactive (selon la méthode VDA 270). De plus, l'influence de la chimie de ces produits sur les propriétés physiques du cuir a été évaluée par des analyses de résistance à la traction, de résistance à la déchirure et de solidité des couleurs après vieillissement accéléré. Les résultats ont révélé des différences significatives entre les produits évalués en ce qui concerne la condensation et les odeurs. Les valeurs gravimétriques pour la formation de condensation s'échelonnaient de 6,8 à 20,8 mg ; les produits synthétiques, à base de phosphoesters et à base de lécithine présentaient généralement une tendance au condensation relativement plus faible, tandis que certaines formulations à base d'huile de poisson ou d'esters affichaient des valeurs plus élevées. Les notes d'odeur variaient entre 3,0 et 4,5, et aucune corrélation directe n'a été observée entre la formation de condensation et la performance olfactive. Il convient de noter que des différences considérables ont également été observées entre des produits commerciaux appartenant à une même classe chimique, ce qui indique que les caractéristiques spécifiques de la formulation jouent un rôle important dans le comportement en matière d'émissions. Ces conclusions démontrent que la chimie et les caractéristiques de formulation des produits de nourrissage doivent être prises en compte avec soin lors de la sélection de produits à faibles émissions pour les cuirs automobiles.
MOTS-CLÉS : cuir automobile, produit de nourrissage, condensation, émission d'odeurs, résistance mécanique

INTRODUCTION

Leather is one of the premium materials in automotive interiors owing to its excellent combination of comfort, durability, flexibility, aesthetic appearance and breathability [1–3]. As consumer expectations and automotive quality standards continue to increase, the performance requirements imposed on automotive leather have become increasingly stringent. In addition to conventional mechanical properties and appearance characteristics, special attention is now given to volatile emissions originating from interior materials because of their influence on passenger comfort, interior air quality and driving safety [4, 5].

Among the emission-related phenomena encountered in automotive interiors, fogging is regarded as one of the most critical quality parameters. Fogging refers to the evaporation of volatile substances from interior materials under elevated temperatures followed by their condensation on cooler surfaces, particularly vehicle windshields [4]. The resulting condensate forms a haze-like layer that may impair visibility and contribute to safety concerns. Since the 1990s, the automotive industry has devoted considerable attention to fogging behaviour, leading to the development of standardized evaluation procedures such as DIN 75201 and subsequently, ISO 17071 for leather materials [4, 5]. Today, fogging performance remains an essential requirement for automotive leather approval.

Leather fogging may originate from various components used on leather goods and during leather manufacture, including finishing chemicals, adhesives, plasticizers and fatliquors [4]. Among these, fatliquors are widely recognized as one of the most significant contributors to fogging behaviour because they contain volatile organic compounds capable of migrating from the leather matrix under thermal conditions [6, 7].

Fatliquors are indispensable chemicals in leather processing, where they lubricate collagen fibres, reduce interfibrillary friction and impart softness, fullness, flexibility, and mechanical strength to the finished leather [8–10]. Recent developments have also focused on the design of functional fatliquors capable of providing additional performance benefits, such as antimicrobial activity, enhanced softness and improved sustainability [10, 11]. Traditionally, fatliquors have been produced from fish oils, vegetable oils, synthetic lubricants, phosphoesters, sulfated oils and various combinations thereof [6, 11].

In addition to fogging, odour emission represents another important quality parameter for automotive leather. Leather is known to release various volatile compounds originating from raw materials, processing chemicals, fatliquors, finishing products, and degradation reactions occurring during manufacture and service life. Although odour does not directly impair visibility, it can significantly affect passenger comfort and perceived product quality. For this reason, odour characteristics of automotive trim materials are commonly evaluated using sensory assessment methods such as VDA 270, which remain widely accepted within the automotive industry. Previous studies have highlighted that leather production has

historically been associated with odour-related concerns and that volatile emissions from leather products can contribute to nuisance and discomfort when not adequately controlled [12].

The relationship between fatliquor chemistry and volatile emissions has attracted increasing scientific interest in recent years. Wang *et al*. (2011) demonstrated that fatty spew and fogging are closely related phenomena and reported that fatty acid methyl esters, particularly methyl palmitate, methyl oleate and methyl stearate, are among the principal compounds associated with these defects [13]. Their findings suggested that highly mobile oil components can migrate from the collagen matrix and contribute to both surface exudation and volatile emissions. Similarly, Li *et al*. (2025) reported that fatliquors possessing low molecular weight, low melting points and high aliphatic ester content exhibit greater migration potential within leather, thereby increasing the risk of fogging-related defects [14].

Recent studies have further revealed that the fogging behaviour of leather is strongly governed by the interaction strength between fatliquor molecules and collagen fibres. Lyu *et al*. (2020) showed that improving the fixation of fatliquors within the collagen network effectively suppresses the migration of low-molecular-weight compounds and significantly reduces fogging values [15]. In another study, the incorporation of polymeric structures and reactive functional groups into fatliquor formulations enhanced leather performance while simultaneously satisfying automotive fogging requirements [16]. Zhang *et al*. (2022) systematically investigated the influence of fatliquor molecular structure on fogging behaviour and demonstrated that the introduction of hydroxyl, amino, and carboxyl functionalities strengthened intermolecular interactions with collagen fibres, thereby reducing migration and lowering fogging values [17]. More recently, phosphorylated and esterquat-based fatliquors have been reported to exhibit stronger interactions with leather fibres, improved fixation and reduced migration compared with conventional fatliquor systems [11, 14].

Despite these important advances, most previous investigations have focused on the synthesis and characterization of newly developed low-fogging fatliquors. Comparatively little information is available regarding the behaviour of commercially available fatliquors currently used by the leather industry. In practice, leather manufacturers employ a wide range of commercial fatliquors differing substantially in their chemical composition, including phosphoester-based, fish-oil-based, ester-based, lecithin-containing and synthetic formulations. However, comprehensive studies correlating the chemical nature of these commercial products with fogging behaviour, odour performance and leather properties remain limited.

Therefore, the objective of the present study was to evaluate the influence of fatliquor chemistry on the fogging and odour characteristics of automotive leather using commercially available fatliquors representing different chemical classes. The findings provide new insights into the relationship between fatliquor composition, migration behaviour, volatile emissions and leather properties, contributing to the development and selection of low-emission fatliquors for automotive leather applications.

MATERIALS AND METHODS

Materials

Wet-blue cattle hides were supplied by DD Demir Deri San. ve Tic. A.Ş. (Bursa, Turkiye). Commercially available fatliquors representing different chemical classes, including phosphoester-based, fish-oil-based, ester-based, lecithin-containing and synthetic formulations were supplied by three different companies from Turkiye. The main properties of the different chemical-based commercial fatliquors used in this study were provided by the three respective chemical manufacturers and are presented in Table 1.

Table 1: Properties of different chemical-based commercial fatliquors

Chemical Class	Commercial Fatliquor	Solids Content (%)	pH (1:10)	Main Characteristics
Phosphoester-based	SUPPLIER 1 (P-SUP1)	47.5	6.5–7.5	High penetration, oxidation resistance, excellent electrolyte and chrome stability, high lightfastness, promotes uniform dyeing and fullness.
	SUPPLIER 2 (P-SUP2)	59.0	6.0–8.0	High penetration and distribution, non-oxidizing character, excellent lightfastness, improves uptake of other fatliquors and dye uniformity.
	SUPPLIER 3 (P-SUP3)	47.0	6.0–7.0	Soft and waxy handle, good hard-water and chrome stability, suitable for white and pastel leathers, improves colour uniformity.
Lecithin-based	SUPPLIER 1 (L-SUP1)	52.5	6.0–7.0	Very soft handle, low specific gravity, silky and warm touch, excellent penetration and dyeing performance.
	SUPPLIER 2 (L-SUP2)	75	6.5–7.5	Very soft and supple handle, silky surface texture, high lightfastness and heat resistance, low odour
	SUPPLIER 3 (L-SUP3)	42.5	6.0–7.5	Soft, warm and slightly moist handle, high penetration, low density.
Fish oil-based	SUPPLIER 1 (F-SUP1)	62.5	6.0–7.0	Soft, full and waxy handle, high penetration, excellent softness and fullness.
	SUPPLIER 2 (F-SUP2)	75	6.0–7.0	Very soft and elastic handle, high electrolyte stability, excellent penetration.
	SUPPLIER 3 (F-SUP3)	65.0	6.0–8.0	High internal softness, silky handle, good brightness and penetration.
Ester-based	SUPPLIER 1 (E-SUP1)	57.5	7.5–8.5	General-purpose fatliquor providing softness and fullness, high lightfastness, improves mechanical strength and grain tightness.
	SUPPLIER 2 (E-SUP2)	70	7.0–8.0	Excellent fullness, tight grain, springy handle, high lightfastness and yellowing resistance, high exhaustion
	SUPPLIER 3 (E-SUP3)	50.0	6.0–7.0	Full handle, medium softness, silky touch, good grain tightness.
Synthetic oil-based	SUPPLIER 1 (S-SUP1)	47.0	6.0–7.0	Soft and full handle, good penetration and distribution, suitable for white and light-coloured leathers.
	SUPPLIER 2 (S-SUP2)	65	6.5–7.5	Full, soft and light handle; very low specific gravity; produces a tight and fine grain; excellent heat and light fastness.
	SUPPLIER 3 (S-SUP3)	48.5	6.0–7.0	High emulsification power, excellent electrolyte stability, promotes penetration of other oils and homogeneous lubrication.

Leather Production

The production recipe for wet-blue (chrome tanned) leathers is outlined in Table 2, covering the processes of neutralization and fatliquoring. To eliminate the influence of retanning and dyeing chemicals on the evaluated properties, all experimental leathers were processed according to a simplified wet-blue formulation containing only 6% fatliquor (based on shaved weight). No retanning agents or dyestuffs were applied. The control sample underwent the same processing conditions but received no fatliquor treatment.

Table 2: Leather production recipe

Process	%	Chemicals	Temperature (°C)	Time (min.)	Remarks
Re-Wetting	200	Water	30		
	1	Acetic acid		40	Drain
Neutralization	100	Water	30		
	1.5	Sodium formate		30	
	0.8	Sodium bicarbonate		2x30	pH 5.2, Drain
Washing x3	200	Water	30		Drain
Fatliquoring	80	Water	50		
	6	Fatliquor agent		60	
	1	Formic acid		60	pH 4
Drain-Washing-Horsing up overnight					

Fogging Test

The fogging characteristics of the leather samples were determined according to DIN EN ISO 17071 using the gravimetric method. Prior to testing, leather specimens were conditioned for 7 days. Two circular test pieces (80 mm diameter) were cut from each sample and placed in glass beakers. An aluminium foil collector was positioned above the specimens and the assembly was maintained at 100 ± 1 °C for 16 h. Volatile compounds released from the leather condensed on the cooled aluminium foil surface. After the test, the aluminium foil was conditioned in a desiccator and reweighed. The fogging value was calculated from the mass increase of the aluminium foil and expressed as milligrams (mg) of condensed volatile material. Lower fogging values indicate lower emission of volatile substances from the leather samples.

Odour Analysis

The odour characteristics of the leather samples treated with different fatliquors were evaluated according to VDA 270 – Determination of the odour characteristics of trim materials in motor vehicles [18]. The VDA 270 method is based on sensory evaluation of material or component specimens after storage in closed test vessels under defined conditions. A standard 1-L glass vessel is used, and the test conditions are selected according to the material and the applicable specification. In the present study, variants D4 and D5 were applied. Both variants involve conditioning of the specimens at 50 °C for 2 h. The distinction between the two variants is the presence of water in the test vessel: D4 is performed with water in the test vessel, whereas D5 is performed without water. Thus, D4 and D5 were used to evaluate the odour characteristics of the leather under humid and dry thermal conditioning, respectively.

Prior to testing, the samples were preconditioned for seven days under standard atmospheric conditions. Test specimens with an approximate size of A4, or an equivalent sample amount of approximately 100 g, were placed in the test vessels and conditioned according to the respective VDA 270 variant.

Odour intensity was evaluated by a six-member sensory panel consisting of three female and three male assessors aged between 27 and 38 years. The odour intensity was rated using the six-point VDA 270 scale, where 1 represents “very weak, not perceptible odour”, 2 “weak, perceptible but not annoying”, 3 “distinct but not annoying”, 4 “strong, annoying”, 5 “very strong, more annoying”, and 6 “extremely strong, extremely annoying and disgusting.” In addition to the numerical intensity rating, qualitative odour descriptors were recorded when applicable.

Physical Properties of Fatliquored Leathers

The tensile properties of the leather samples, including tensile strength and percentage elongation at break were evaluated in accordance with TS EN ISO 3376. Tear resistance was determined according to TS EN ISO 3377-1 using the single-edge tear method. All mechanical measurements were carried out using a Shimadzu AG-IS universal testing machine. The resistance of leather samples to colour change under accelerated ageing conditions was evaluated according to TS EN ISO 17228 standard method. Test specimens were exposed in a ventilated laboratory oven under controlled temperature conditions. Two ageing conditions were applied: 60 ± 2 °C for 72 ± 1 h and 100 ± 2 °C for 144 ± 1 h (TS EN ISO 17228-Method 6C and 6D). After ageing, the specimens were conditioned under standard laboratory conditions and visually assessed against the unaged reference specimens. Colour change was evaluated using the grey scale for colour change and reported as grey scale ratings.

RESULTS AND DISCUSSION

The gravimetric fogging values of the leathers treated with different commercial fatliquors are presented in Table 3.

Table 3: Gravimetric fogging values of leathers treated with different commercial fatliquors

Chemical Class	Sample Code	Fogging Value (mg)
Phosphoester-based	P-SUP1	11.70 ± 1.24
	P-SUP2	11.20 ± 0.37
	P-SUP3	8.40 ± 0.72
Lecithin-based	L-SUP1	8.00 ± 0.29
	L-SUP2	9.80 ± 0.47
	L-SUP3	9.50 ± 0.19
Fish oil-based	F-SUP1	10.80 ± 1.16
	F-SUP2	15.20 ± 1.35
	F-SUP3	9.00 ± 0.89
Ester-based	E-SUP1	12.50 ± 0.31
	E-SUP2	11.20 ± 0.15
	E-SUP3	12.80 ± 0.37
Synthetic oil-based	S-SUP1	6.80 ± 0.34
	S-SUP2	8.70 ± 0.20
	S-SUP3	20.80 ± 0.19

Considerable differences were observed among the evaluated samples, with fogging values ranging from 6.8 to 20.8 mg. This wide variation clearly indicates that the chemical nature of the fatliquor plays a decisive role in the emission behaviour of automotive leather. Since all leathers were processed using the same wet-blue substrate and identical processing recipe, except for the fatliquor type, the differences in fogging performance can mainly be attributed to the composition, volatility, molecular mobility and collagen-binding ability of the fatliquors listed in Table 1.

Among the phosphoester-based fatliquors, P-SUP3 showed the lowest fogging value (8.4 mg), followed by P-SUP2 (11.2 mg) and P-SUP1 (11.7 mg). Phosphoester-based fatliquors are generally expected to exhibit improved fixation within the collagen matrix due to their polar phosphate-containing groups, which may enhance interaction with chrome-tanned collagen fibres. This is consistent with recent findings indicating that phosphorylated fatliquors can show stronger interactions with leather fibres and lower migration tendency compared with conventional oil-based systems [14]. However, the differences among P-SUP1, P-SUP2 and P-SUP3 demonstrate that the presence of phosphoester functionality alone is not sufficient to determine fogging behaviour. Other formulation parameters, such as active matter content, the proportion of natural or synthetic oil components, emulsifier type and the presence of low-molecular-weight fractions, may also influence the amount of volatile material released during heating.

The lecithin-based group exhibited relatively low and close fogging values, ranging from 8.0 to 9.8 mg. L-SUP1 gave the lowest value within this group (8.0 mg), while L-SUP2 and L-SUP3 showed fogging values of 9.8 and 9.5 mg, respectively. According to Table 1, these products are characterized by soft handle, high penetration, low density and good dyeing behaviour. Lecithin-containing fatliquors may provide effective lubrication and fibre distribution due to their polar phospholipid structure. The comparatively narrow fogging range of this group suggests that lecithin-based systems may offer a balanced combination of softness and moderate emission behaviour. Nevertheless, despite their favourable handle properties, their fogging values remained higher than the best-performing synthetic oil-based product, indicating that low fogging cannot be predicted solely from softness or penetration ability.

Fish-oil-based fatliquors showed more variable fogging behaviour. F-SUP3 exhibited the lowest fogging value in this group (9.0 mg), whereas F-SUP1 and F-SUP2 showed higher values of 10.8 and 15.2 mg, respectively. Fish-oil-based fatliquors are traditionally known for imparting excellent softness, fullness, waxy handle and internal lubrication, as also summarized in Table 1. However, their chemical structure, typically rich in long-chain unsaturated fatty components, may also increase the risk of oxidation, degradation and migration under thermal conditions. The

relatively high fogging value of F-SUP2 suggests the presence of more mobile or volatile oil fractions, despite its high penetration and electrolyte stability. This agrees with the general understanding that fatliquors containing weakly bound oil components can migrate from the leather matrix and contribute to fogging formation [6, 7]. Wang *et al*. (2013) also reported that fatty acid methyl esters associated with fatliquor composition may contribute to both fatty spew and fogging phenomena [13].

In the ester-based group, fogging values were relatively close to each other, with E-SUP1, E-SUP2 and E-SUP3 giving values of 12.5, 11.2 and 12.8 mg, respectively. These results indicate that ester-based fatliquors showed moderate-to-high fogging tendency compared with lecithin-based and some phosphoester-based systems. As shown in Table 1, this group is associated with fullness, tight grain, springy handle, lightfastness and yellowing resistance. However, ester-rich structures may contain relatively mobile aliphatic ester fractions, which can migrate more readily under elevated temperature. This interpretation is supported by Li *et al*. (2025), who reported that fatliquors with low molecular weight, low melting point and high aliphatic ester content exhibit greater migration potential within leather [14]. Therefore, although ester-based fatliquors may provide desirable physical and handle properties, their formulation should be carefully optimized for automotive leather applications where low emission performance is required.

The synthetic oil-based group showed the widest variation in fogging behaviour. S-SUP1 exhibited the lowest fogging value among all tested samples (6.8 mg), whereas S-SUP3 showed the highest value (20.8 mg). S-SUP2 also displayed a relatively low fogging value of 8.7 mg. This result is particularly important because it demonstrates that synthetic oil-based classification alone does not guarantee low fogging performance. The markedly high value of S-SUP3 may be related to its strong emulsification capacity and ability to promote penetration of other oils, as indicated in Table 1. Although such characteristics are technologically advantageous for homogeneous lubrication, they may also facilitate the mobility of low-molecular-weight or weakly fixed oil components within the leather matrix. In contrast, S-SUP1 and S-SUP2 appear to contain less volatile or better-fixed components, resulting in substantially lower fogging values.

The results in Table 3 show that the fogging behaviour of fatliquored automotive leather is governed by a combination of fatliquor chemistry, molecular mobility, volatility and interaction with collagen fibres. The lowest fogging values were obtained with S-SUP1, L-SUP1, P-SUP3 and S-SUP2, while the highest values were observed for S-SUP3 and F-SUP2. These findings support the concept that low fogging is not determined only by the general chemical class of the fatliquor, but by the specific formulation chemistry within each class.

Odour is a critical quality parameter for automotive interior materials because it directly influences passenger comfort and perceived product quality. Unlike fogging, which primarily affects visibility and safety, odour emissions influence consumer acceptance and can lead to rejection of otherwise technically satisfactory materials. The odour characteristics of the leather samples produced with different commercial fatliquors are presented in Table 4.

Table 4: Odour characteristics of leathers treated with different commercial fatliquors

Chemical Class	Sample Code	D4 Rating	D4 Odour Description	D5 Rating	D5 Odour Description
	P-SUP1	4.0	Pungent	3.0	None
Phosphoester-based	P-SUP2	3.0	Fatty, fruity	3.5	Nut-like
	P-SUP3	3.5	Burnt, sour	3.5	Coffee-like
	L-SUP1	4.0	Pungent, sour	3.5	None
Lecithin-based	L-SUP2	4.0	None	3.5	None
	L-SUP3	3.5	Musty, old	3.0	None
	F-SUP1	3.0	None	3.0	None
Fish oil-based	F-SUP2	3.5	Fecal	3.0	None
	F-SUP3	3.5	Fruity, chemical, fecal	4.0	Chemical, fecal

Chemical Class	Sample Code	D4 Rating	D4 Odour Description	D5 Rating	D5 Odour Description
	E-SUP1	3.5	Fatty, fruity	3.0	None
Ester-based	E-SUP2	3.5	Fatty	3.0	None
	E-SUP3	4.0	Fecal	3.5	Fecal
	S-SUP1	4.5	Fecal, sour	4.0	Fecal
Synthetic oil-based	S-SUP2	3.0	None	3.0	None
	S-SUP3	3.0	Fatty	3.0	None

The D4 odour ratings of the investigated leathers ranged from 3.0 to 4.5, while D5 ratings varied between 3.0 and 4.0 (Table 4). These results demonstrate that fatliquor chemistry has a significant influence on the sensory characteristics of automotive leather. However, unlike the fogging results presented in Table 3, the odour ratings did not show a direct relationship with gravimetric fogging values, indicating that the mechanisms governing volatile mass emission and odour perception are not necessarily identical. Among the phosphoester-based fatliquors, P-SUP2 exhibited the lowest D4 rating (3.0), while P-SUP1 and P-SUP3 showed slightly higher values of 4.0 and 3.5, respectively. The odour descriptors associated with this group included pungent, fatty, fruity, burnt and sour notes. Interestingly, although all three products belong to the same chemical class and displayed relatively similar fogging behaviour (Table 3), their odour profiles differed considerably. This finding suggests that odour perception is influenced not only by the total quantity of emitted substances but also by the chemical identity of specific volatile compounds. Small amounts of highly odorous substances may significantly affect sensory evaluation even when overall volatile emissions remain relatively low.

The lecithin-based fatliquors produced moderate odour ratings. L-SUP1 and L-SUP2 both exhibited D4 values of 4.0, whereas L-SUP3 showed a lower value of 3.5. Lecithin-containing systems contain phospholipid structures that generally provide good lubrication and compatibility with collagen fibres. Nevertheless, the presence of natural lipid fractions may contribute to the formation of characteristic odour compounds during thermal conditioning. The pungent and sour notes observed for L-SUP1 and the musty odour detected for L-SUP3 may originate from oxidation products of natural oil components or residual low-molecular-weight compounds present in the formulation.

The fish-oil-based group exhibited particularly interesting behaviour. F-SUP1 showed the lowest odour intensity among all tested samples, with D4 and D5 ratings of 3.0 and no detectable odour descriptors. In contrast, F-SUP2 and especially F-SUP3 generated more pronounced odour characteristics, including fecal, fruity and chemical notes. Fish-oil-based fatliquors are traditionally valued for their excellent softness and lubrication properties (Table 1), but they may also contain unsaturated fatty components susceptible to oxidative degradation. The formation of aldehydes, ketones and short-chain oxidation products during thermal exposure can contribute significantly to odour generation. The markedly different behaviour observed among the three fish-oil-based products further demonstrates that formulation details and purification level may be more important than the general chemical class itself.

The ester-based fatliquors generally exhibited acceptable odour performance, with D4 ratings between 3.5 and 4.0. E-SUP1 and E-SUP2 were characterized primarily by fatty and fruity notes, whereas E-SUP3 produced a more pronounced fecal odour. As indicated in Table 1, ester-based products are designed to provide fullness, grain tightness and favourable handle properties. However, ester-containing formulations may generate volatile decomposition products under elevated temperatures, particularly when low-molecular-weight ester fractions are present. The higher odour intensity observed for E-SUP3 suggests that the composition of the ester fraction plays a significant role in determining sensory performance.

The synthetic oil-based group displayed the greatest variation in odour behaviour. S-SUP2 and S-SUP3 exhibited the lowest odour

ratings (3.0), whereas S-SUP1 produced the highest odour intensity among all evaluated samples, with D4 and D5 ratings of 4.5 and 4.0, respectively. Notably, S-SUP1 also exhibited the lowest fogging value in Table 3 (6.8 mg). This observation clearly demonstrates that low fogging does not necessarily correspond to low odour. Although S-SUP1 emitted relatively small quantities of volatile material, the emitted compounds apparently possessed a high odour impact and were perceived as fecal and sour by the sensory panel. Conversely, S-SUP3 exhibited the highest fogging value (20.8 mg) while receiving one of the lowest odour ratings. Such behaviour highlights the fundamental difference between gravimetric fogging measurements and sensory odour evaluation. Fogging quantifies the mass of condensed volatile substances, whereas odour assessment depends on the sensory threshold and perception of specific compounds.

A comparison of Tables 3 and 4 reveals that no direct correlation exists between fogging values and odour ratings. For example, S-SUP1 exhibited the lowest fogging value but the highest odour intensity, whereas S-SUP3 exhibited the highest fogging value but one of the lowest odour ratings. Similarly, F-SUP1 demonstrated moderate fogging behaviour while producing the most favourable odour performance. These findings suggest that fogging and odour should be evaluated as complementary but independent parameters when assessing automotive leather emissions.

The tensile strength, elongation at break and tear strength values of the experimental leathers are presented in Table 5.

Table 5: Strength properties of leathers treated with different commercial fatliquors

Chemical Class	Sample Code	Tensile Strength (N/mm²)	Elongation (%)	Single Tear Load (N)
	P-SUP1	26.00 ± 0.85	70.30 ± 1.45	47.30 ± 1.20
Phosphoester-based	P-SUP2	21.40 ± 0.72	73.20 ± 1.80	76.20 ± 2.15
	P-SUP3	23.50 ± 1.68	68.60 ± 2.25	65.40 ± 1.90
	L-SUP1	27.50 ± 0.90	70.20 ± 1.35	55.10 ± 1.65
Lecithin-based	L-SUP2	26.40 ± 0.78	71.50 ± 1.60	48.50 ± 1.40
	L-SUP3	27.00 ± 0.82	68.70 ± 1.50	50.10 ± 1.30
	F-SUP1	25.80 ± 0.75	65.40 ± 1.20	75.40 ± 2.10
Fish oil-based	F-SUP2	26.40 ± 0.88	68.70 ± 1.65	73.20 ± 1.95
	F-SUP3	28.70 ± 0.95	72.40 ± 1.70	68.40 ± 1.80
	E-SUP1	26.70 ± 2.80	79.00 ± 2.10	80.00 ± 2.30
Ester-based	E-SUP2	25.40 ± 1.70	75.80 ± 1.85	82.40 ± 2.45
	E-SUP3	18.60 ± 0.65	71.60 ± 1.55	59.10 ± 1.75
	S-SUP1	29.50 ± 2.05	72.40 ± 1.60	52.40 ± 1.50
Synthetic oil-based	S-SUP2	31.50 ± 3.12	75.60 ± 2.90	59.50 ± 1.65
	S-SUP3	32.20 ± 1.18	78.10 ± 2.05	57.00 ± 1.60
Control	Control	25.60 ± 0.82	63.10 ± 1.30	47.30 ± 1.25

All fatliquored samples exhibited higher elongation values than the control leather, confirming the beneficial lubricating effect of fatliquors on collagen fibre mobility and flexibility. The control sample showed an elongation value of 63.1%, whereas the fatliquored leathers exhibited elongation values ranging from 65.4% to 79.0%, demonstrating that the incorporation of lubricating agents effectively reduced interfibrillar friction within the collagen network.

Significant differences were observed in tensile strength depending on fatliquor chemistry. The highest tensile strength values were obtained for the synthetic oil-based group, particularly S-SUP3 (32.2 N/mm²), S-SUP2 (31.5 N/mm²) and S-SUP1 (29.5 N/mm²), all of which exceeded the control value of 25.6 N/mm². According to the characteristics summarized in Table 1, synthetic oil-based fatliquors are designed to provide homogeneous lubrication, high emulsification stability and effective penetration into the leather structure. These properties may contribute to a more uniform stress distribution during tensile loading, resulting in improved tensile performance. The superior behaviour of the synthetic oil-based products suggests that efficient fibre lubrication and

homogeneous oil distribution play a critical role in maximizing tensile strength. The lecithin-based fatliquors also exhibited relatively high tensile strength values, ranging from 26.4 to 27.5 N/mm². The highest value within this group was observed for L-SUP1 (27.5 N/mm²). Lecithin-containing systems are characterized by excellent penetration and softening ability (Table 1), which may facilitate uniform fibre lubrication without excessive fibre separation. The relatively narrow variation observed within this group indicates a consistent effect of lecithin-containing formulations on tensile performance.

A different trend was observed for tear strength. The highest tear resistance values were obtained with the ester-based fatliquors, particularly E-SUP2 (82.4 N) and E-SUP1 (80.0 N), followed by P-SUP2 (76.2 N), F-SUP1 (75.4 N) and F-SUP2 (73.2 N). These values were substantially higher than the control sample (47.3 N). The superior tear strength of the ester-based group may be associated with the fullness, grain tightness and structural reinforcement characteristics reported in Table 1. Within the phosphoester-based group, P-SUP2 displayed a remarkable tear strength value (76.2 N) despite exhibiting only moderate tensile strength (21.4 N/mm²). Ester-based fatliquors are specifically formulated to improve grain compactness and fibre cohesion, which can enhance resistance against localized stress concentration during tearing. This observation is consistent with the technical characteristics of E-SUP1 and E-SUP2, which emphasize fullness, tight grain structure and mechanical reinforcement.

Interestingly, the sample exhibiting the highest tensile strength (S-SUP3) did not show the highest tear strength, whereas E-SUP2 exhibited the highest tear resistance despite only moderate tensile strength. This finding highlights the different structural requirements governing tensile and tear properties. Tensile strength is influenced primarily by overall fibre cohesion and stress distribution, whereas tear strength is more closely associated with fibre mobility, fibre interlocking and the ability of the collagen network to dissipate localized stresses. Similar observations have been reported in previous studies, where different fatliquor chemistries affected tensile and tear properties through distinct lubrication mechanisms [9, 16].

Another noteworthy observation is the absence of a direct relationship between mechanical performance and emission behaviour. For example, S-SUP3 exhibited the highest tensile strength but also the highest fogging value (20.8 mg) in Table 3, whereas S-SUP1 combined the lowest fogging value (6.8 mg) with excellent tensile performance. Similarly, E-SUP2 provided the highest tear strength despite only moderate fogging behaviour. These results indicate that high mechanical performance does not necessarily correspond to low-emission characteristics and vice versa. Therefore, the selection of automotive fatliquors should be based on a balanced evaluation of both physical performance and emission-related properties.

The resistance of the leather samples to colour change after accelerated ageing is presented in Table 6. The grey scale ratings obtained after ageing at 60 °C for 72 h and 100 °C for 144 h revealed noticeable differences among the evaluated fatliquor systems.

Table 6: Colour change assessment of leather samples after accelerated ageing

Chemical Class	Sample Code	60°C ± 2°C / 72 h ± 1 h	100°C ± 2°C / 144 h ± 1 h
	P-SUP1	3/4	2/3
Phosphoester-based	P-SUP2	3	2
	P-SUP3	3	2
	L-SUP1	3	1/2
Lecithin-based	L-SUP2	3	1/2
	L-SUP3	3	1
	F-SUP1	3	2
Fish oil-based	F-SUP2	2/3	2
	F-SUP3	3	2
	E-SUP1	3	2
Ester-based	E-SUP2	2	2
	E-SUP3	1/2	1/2

Chemical Class	Sample Code	60°C ± 2°C / 72 h ± 1 h	100°C ± 2°C / 144 h ± 1 h
	S-SUP1	3/4	3
Synthetic oil-based	S-SUP2	4	3/4
	S-SUP3	3/4	3/4
Control	Control	3/4	2/3

Among the investigated fatliquors, the synthetic oil-based group demonstrated the best overall ageing performance. S-SUP2 exhibited the highest colour stability, with grey scale ratings of 4 and 3/4 under mild and severe ageing conditions, respectively. Similarly, S-SUP1 and S-SUP3 maintained relatively high ratings throughout the ageing process. These results are consistent with the excellent heat and light fastness characteristics reported for synthetic oil-based products in Table 1. The phosphoester-based fatliquors also showed good resistance to colour change. P-SUP1 exhibited ageing performance comparable to the control leather, while P-SUP2 and P-SUP3 showed only slightly lower ratings. The favourable behaviour of this group may be attributed to their oxidation resistance and high lightfastness properties.

In contrast, lecithin-based and ester-based fatliquors generally exhibited lower ageing resistance. The most pronounced colour deterioration was observed for E-SUP3, which showed grey scale ratings of only 1/2 under both ageing conditions. Similarly, L-SUP3 displayed substantial colour change after severe ageing, indicating a higher susceptibility to thermal oxidation.

The results indicate that synthetic oil-based and phosphoester-based fatliquors provide superior colour stability, whereas certain lecithin-based and ester-based formulations are more prone to thermal discoloration. These findings demonstrate that, in addition to fogging, odour and mechanical performance, ageing resistance should also be considered when selecting fatliquors for automotive leather applications.

CONCLUSIONS

This study comparatively evaluated the influence of eleven commercial fatliquors from three different suppliers representing phosphoester-based, lecithin-based, fish oil-based, ester-based and synthetic oil-based systems on the fogging, odour, mechanical and ageing performance of automotive leather.

The results demonstrated that fatliquor chemistry plays a decisive role in the fogging behaviour of automotive leather. Gravimetric fogging values varied from 6.8 to 20.8 mg, revealing substantial differences among commercially available formulations. In general, synthetic oil-based, phosphoester-based and lecithin-based fatliquors exhibited lower fogging tendencies, whereas certain fish oil-based and ester-based formulations showed comparatively higher fogging values. However, significant variations were also observed among products belonging to the same chemical class, indicating that fogging behaviour is governed not only by the general fatliquor type but also by formulation-specific characteristics such as molecular composition, volatility, migration tendency and interaction with collagen fibres.

Odour ratings ranged between 3.0 and 4.5, confirming that fatliquor composition strongly influences the sensory characteristics of automotive leather. No direct relationship was observed between fogging and odour performance, demonstrating that the amount of emitted volatile material and its sensory perception are controlled by different mechanisms. Consequently, fogging and odour should be considered as complementary but independent evaluation parameters in automotive leather assessment.

The mechanical performance of leather was also affected by fatliquor chemistry. Synthetic oil-based formulations generally produced the highest tensile strength values, while ester-based fatliquors provided superior tear resistance and elongation. Furthermore, synthetic oil-based and phosphoester-based systems exhibited the highest resistance to colour change after accelerated ageing, indicating superior thermal stability compared with several lecithin-based and ester-based formulations.

The findings demonstrate that the selection of fatliquors for automotive leather should not be based solely on softness and handle characteristics. Instead, a balanced evaluation of fogging, odour, mechanical performance and ageing resistance is required. The results provide valuable guidance for leather manufacturers and chemical suppliers in the development of low-emission fatliquor systems capable of meeting increasingly stringent automotive performance requirements.

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