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Quaternary ammonium nonanoate-based ionic liquids as chemicals for crop protection

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ABSTRACT

The use of renewable chemicals has become one of the most rapidly developing trends in chemical synthesis. Numerous naturally occurring compounds become green alternatives for traditional oleochemicals due to the fact that they exhibit a wide range of attractive properties. Substances such as pelargonic (nonanoic) acid, which are obtained as secondary metabolites from plants or microorganisms, play a major role in their defense systems by protecting them from diseases, herbivores or predators. Therefore, due to their unique biological properties, the natural chemicals are potential components of ionic liquids (ILs). In this study, the synthesis and properties of ammonium ILs with nonanoate anion are presented. The reactions were conducted in a short time under ambient temperature and pressure. The products were obtained with high yields. The synthesized ILs were characterized by good surface active properties. Didecyldimethylammonium nonanoate reduced the surface tension of water to 21.86 mN/m. The feeding deterrence activity of the obtained nonanoates was also examined and the studied ILs exhibited high feeding deterrence activity, comparable to natural occurring antifeedants, azadirachtin. Additionally, the synthesized ILs were also active towards rods, cocci and fungi. The obtained results allowed to link surface properties with biological activity of synthesized ILs.

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1. Introduction

Quaternary ammonium compounds (QACs) or quaternary ammonium salts (quats) are the products of reaction of tertiary amines with alkyl halides. This universal synthesis method, also known as the Menschutkin reaction, was first described at the end of 19th century [1,2]. Jacobs and Heidelberger first discovered the antibacterial effect of QACs [3]. In 1935 Domagk synthesized long-chain QACs and characterized their antibacterial activities [4]. In the 20th century scientists have focused on water soluble QACs (chlorides and bromides) due to the fact that they exhibit a wide range of interesting properties. They are cationic surfactants, which destroy bacteria and fungi, serve as catalysts during phase-transfer catalysis and exhibit antistatic and anticorrosive properties. At present, QACs are still widely used as skin antiseptics, disinfectants, fabric softeners, antistatic agents, cleaning agents and preservatives. Benzalkonium chloride (BA), didecyldimethylammonium chloride (DDA) or hexadecyltrimethylammonium bromide (CET) are active ingredients in the compositions of cleaning products. Their low toxicity to warm-blooded organisms makes them safe, effective and low-cost antimicrobials. By the end of the 20th century, due to the works of Rogers and Seddon, QACs with a melting point below 100 °C were qualified as ionic liquids (ILs) [5,6]. Intensively studied and widely spread in the 20th century, quaternary ammonium chlorides and bromides are commonly described as precursors of ILs.

Synthesis of ILs gives an opportunity to obtain products with desired physicochemical characteristics. The basic properties of ILs, such as density, viscosity or electrochemical conductivity, are determined by their structure [7]. Appropriate combination of cation-anion coupling creates ILs for use in electrochemistry [8,9] or organic synthesis, both as solvents and catalysts [10,11]. After many years of developing ILs for technological purposes, it has been noted that ILs may exhibit high biological activity. This group of ILs, considered as III generation of ILs, is developing rapidly in recent years [12,13].

Biological activity towards bacteria and fungi has been stated for certain ILs [14-16]. Use of ILs as pharmaceutics is based on the process of transforming active substances to an ionic form and proper selection of counter ions [17,18]. This strategy leads to ILs with antitumor, antibiotic or anesthetic properties [19,20]. The transformation of active substances to ILs is not only limited to pharmacy.

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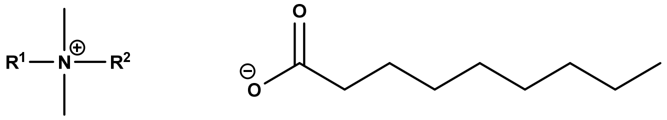
Table 1. Synthesis and thermal properties of quaternary ammonium nonanoates *.



R^1: $C_{10}H_{21}$ or benzyl or CH_3, R^2: $C_{10}H_{21}$ or alkyl (60% $C_{12}H_{25}$ and 40% $C_{14}H_{29}$) or $C_{16}H_{33}$

Nonanoate	R¹	R²	Yield [%]	T_g [°C]	T_c [°C]	T_m [°C]	$T_{onset5\%}$ [°C]	$T_{onset50\%}$ [°C]
1	$C_{10}H_{21}$	$C_{10}H_{21}$	92	-	18	33	180	260
2	Benzyl	Alkyl	91	-	-12	-6	175	243
3	$C_{16}H_{33}$	CH_3	95	20	93	96	193	231

* T_g-glass transition, T_c-crystallization temperature, T_m-melting temperature, $T_{5\%}$-decomposition temperature to 5% weight loss, $T_{50\%}$-decomposition temperature to 50% weight loss.

Conversion of compounds widely used in agriculture - herbicides, fungicides, growth regulators is also possible. Known herbicides, such as phenoxyacetic acids (2,4-D, MCPA, MCPP and MCPB), dicamba, clopyralid, fomesafen, glyphosate, metsulfuron methyl, or bentazone, have been successfully transformed into ILs, which resulted in increased efficiency, lower environmental impact and reduced required dose per hectare [21-32]. Combination of herbicidal activity of the anion with different properties of the cation leads to dual-function ILs [33]. ILs can also be used for protection of crops against pathogenic fungi-transforming fungicides, such as tebuconazole and propiconazole, results in efficient fungicidal ILs with improved physicochemical properties [34].

ILs also have the potential to be used also in protection of harvested grains from insects by acting as feeding deterrents. Deterrent activity is described as the ability to temporary or constantly disrupt the feeding and reproduction processes of an organism without killing it. Substances which exhibit deterrent activity are common in nature and occur in many plants [35]. Azadirachtin, obtained from *Azadirachta indica,* is one of the most efficient deterrent, however attempts to synthesize it under laboratory conditions require complicated reactions which involve many steps [36]. In search for cheap and efficient deterrents, ILs have been proposed as alternatives [37,38]. Based on the knowledge regarding the unique properties of naturally occurring substances, ILs with natural anions-theophyllinates and carboxylates have been synthesized and examined as feeding deterrents [39,40].

The main concern associated with the use of large amounts of ILs, i.e. in agriculture, is their effect on environment [41]. Efficient use of ILs should compromise high biological activity directed to specific pests with negligible impact on other organisms present in soil or water. General procedures for the synthesis of non-toxic and environmental friendly ILs have been established on the basis of several studies dedicated to this topic [42]. The use of ionic forms of substances commonly present in nature may be an alternative way to lower the toxicity and improve the biodegradability of ILs, since such substances are often characterized by promising properties [40,43]. Their potential use in various applications became one of the most popular trends in science [44]. The use of such substances in chemical synthesis is considered as a key factor in order to obtain low-cost and environmentally friendly compounds. Examples of this strategy, i.e. synthesis of terpenoid lactones from perillyl alcohols [45] or dialkoxybenzenes from benzenediols [46], show the benefits of using natural active substrates.

Nonanoic acid (pelargonic acid) is one of such substances. In nature, it occurs in many plants and is readily biodegradable and non-toxic at small doses, however it is irritant for the skin. In the industry, this acid is used in organic synthesis, pharmaceuticals, lubricants and plasticizers. Moreover, it has a number of promising properties, such as its high non-selective herbicidal activity. Nonanoic acid is usually used as in the form of an ammonium salt or in combinations with glyphosate, another non-selective herbicide. It is also effective as a fungicide [47].

In this study, ammonium ILs with nonanoate anion are presented as efficient antimicrobials and food deterrents. Nonanoic acid, which is commonly present in nature and exhibits a wide range of properties, was introduced into the structure of ILs as an anion. As shown in previous study, the introduction of an anion of natural origin into ILs resulted in changed physicochemical characteristics and biological properties of the prepared products [40]. Therefore, there is strong need to seek novel sources of anions, which would influence these parameters in the most optimal manner and allow to obtain ILs with a wide range of biological activity and low environmental impact at the same time.

2. Experimental

2.1. Materials

Didecyldimethylammonium chloride (50% in water), benzalkonium chloride (60% $C_{12}H_{25}$, 40% $C_{14}H_{29}$, purity 97%), hexadecyltrimethylammonium chloride (97%), potassium hydroxide (95%), nonanoic acid (95%) and solvents were purchased from Sigma-Aldrich and Avantor and used as obtained.

2.2. Instrumentation

^{1}H NMR spectra were recorded using a Mercury Gemini 300 spectrometer operating at 300 MHz with TMS as the internal standard. ^{13}C NMR spectra were obtained with the same instrument at 75 MHz. The purity of the synthesized nonanoates was determined by CHN elemental analysis and analysis of NMR spectra.

2.3. Synthesis

Quaternary ammonium salts were synthesized in two steps reaction. The process parameters were monitored using Mettler-Toledo EasyMax 102. Reactions were conducted under ambient temperature and pressure. The first stage of the reaction was the synthesis of quaternary ammonium hydroxide by ion exchange reaction between the corresponding quaternary ammonium chloride (didecyldimethyl ammonium - DDA, benzalkonium - BA or hexadecyltrimethyl ammonium - CET) and a stoichiometric amount of potassium hydroxide in 2-propanol as solvent. Reagents were mixed for 15 min at room temperature. KCl was filtered off and the obtained quaternary ammonium hydroxide was then used in a reaction with a stoichiometric amount of nonanoic acid. Neutral pH of the mixture indicated the end of the reaction. The solvent was evaporated under reduced pressure and the obtained product was dried under vacuum (0.1 bar) at 40 °C for 8 h (Table 1).

Didecyldimethylammonium nonanoate (**1**): Color: White. Yield: 92%. ^{1}H NMR (300 MHz, $\mathrm{CDCl_3}$, δ, ppm): 0.88 (m, 9H, $\mathrm{C}H_3\text{-}\mathrm{CH_2}$), 1.26 (m, 38H, $\mathrm{CH_3\text{-}C}H_2$), 1.59 (m, 4H, $\mathrm{C}H_2\text{-}\mathrm{CH_2\text{-}N}$), 1.66 (m, 2H, $\mathrm{C}H_2\text{-}\mathrm{CH_2\text{-}COO^-}$), 2.15 (m, 2H, $\mathrm{C}H_2\text{-}\mathrm{COO^-}$), 3.32 (s, 6H, $\mathrm{C}H_3\text{-}\mathrm{N}$), 3.40 (m, 4H, $\mathrm{C}H_2\text{-}\mathrm{N}$). ^{13}C NMR (75 MHz, $\mathrm{CDCl_3}$, δ, ppm): 179.9 (1C, $C\mathrm{OOH}$), 63.6 (2C, $(C\mathrm{H_2})_2\mathrm{N}$), 51.5 (2C, $(C\mathrm{H_3})_2\mathrm{N}$), 39.4 (1C, $C\mathrm{H_2COO}$), 32.1 (3C, $\mathrm{(CH_3CH_2}C\mathrm{H_2(CH_2)_7)_2N}$, $C\mathrm{H_2(CH_2)_5COO}$), 29.7 (4C, $\mathrm{(CH_3(CH_2)_2(}C\mathrm{H_2)_2(CH_2)_5)_2N}$), 29.5 (7C, $\mathrm{(CH_3(CH_2)_4(}C\mathrm{H_2)_2(CH_2)_3)_2N}$, $(C\mathrm{H_2)_3(CH_2)_2COO}$), 26.6 (2C, $\mathrm{(CH_3(CH_2)_7}C\mathrm{H_2CH_2)_2N}$), 25.6 (1C, $C\mathrm{H_2CH_2COO}$), 22.9 (5C, $\mathrm{(CH_3}C\mathrm{H_2(CH_2)_5}C\mathrm{H_2(CH_2)_2)_2N}$, $C\mathrm{H_2(CH_2)_6COO}$), 14.3 (3C, $(C\mathrm{H_3(CH_2)_9)_2N}$, $C\mathrm{H_3(CH_2)_7COO}$). Anal. calc. for $\mathrm{C_{31}H_{65}NO_2}$: C, 76.95; H, 13.54; N, 2.89. Found: C, 77.28; H, 13.21; N, 3.15%.

Benzalkonium nonanoate (**2**): Color: White. Yield: 91%. ^{1}H NMR (300 MHz, $\mathrm{CDCl_3}$, δ, ppm): 0.86 (m, 6H, $\mathrm{C}H_3\text{-}\mathrm{CH_2}$), 1.25 (m, 26H, $\mathrm{CH_3\text{-}CH_2}$), 1.62 (m, 2H, $\mathrm{C}H_2\text{-}\mathrm{CH_2\text{-}N}$), 1.76 (m, 2H, $\mathrm{C}H_2\text{-}\mathrm{CH_2\text{-}COO}$), 2.18 (t, *J* 15.6, 2H, $\mathrm{CH_2\text{-}C}H_2\text{-}\mathrm{COO}$); 3.25 (s, 6H, $\mathrm{C}H_3\text{-}\mathrm{N}$); 3,38 (m, 2H, $\mathrm{CH_2\text{-}C}H_2\text{-}\mathrm{N}$); 4.90 (s, 2H, $\mathrm{ArC}H_2\mathrm{N}$); 7.43 (m, 3H, Ar-*H*); 7.60 (m, 2H, Ar-*H*). ^{13}C NMR (75 MHz, $\mathrm{CDCl_3}$, δ, ppm): 179.5 (1C, $C\mathrm{OO}$), 133.0 (2C, Ar-*C*), 130.2 (1C, Ar-*C*), 128.9 (2C, Ar-*C*), 127.6 (1C, Ar-*C*), 67.2 (1C, $\mathrm{Ar\text{-}}C\mathrm{H_2N}$), 63.0 (1C, $C\mathrm{H_2N}$), 49.5 (2C, $(C\mathrm{H_3})_2\mathrm{N}$), 39.3 (1C, $C\mathrm{H_2COO}$), 31.8 (2C, $C\mathrm{H_2(CH_2)_{10}N}$, $C\mathrm{H_2(CH_2)_5COO}$), 29.4 (1C, $C\mathrm{H_2(CH_2)_2COO}$), 29.2 (1C, $C\mathrm{H_2(CH_2)_7N}$), 29.1 (2C, $(C\mathrm{H_2)_2(CH_2)_3COO}$), 27.1 (1C, $C\mathrm{H_2(CH_2)_2N}$), 26.2 ($(C\mathrm{H_2CH_2COO}$), 25.2 (1C, $C\mathrm{H_2CH_2N}$), 22.5 (2C, $C\mathrm{H_2(CH_2)_{11}N}$, $C\mathrm{H_2(CH_2)_6COO}$, 13.9 (2C, $C\mathrm{H_3(CH_2)_{12}N}$, $C\mathrm{H_3(CH_2)_7COO}$).

Hexadecyltrimethylammonium nonanoate (**3**): Color: White. Yield: 95%. M.p.: 94-96 °C. ^{1}H NMR (300 MHz, $\mathrm{CDCl_3}$, δ, ppm): 0.96 (m, 6H, $\mathrm{C}H_3\text{-}\mathrm{CH_2}$), 1.29 (m, 32H, $\mathrm{CH_3\text{-}C}H_2$), 1.33 (m, 4H, $\mathrm{C}H_2\text{-}\mathrm{CH_2\text{-}CH_2\text{-}N}$, $\mathrm{C}H_2\text{-}\mathrm{CH_2\text{-}CH_2\text{-}COO}$), 1.62 (m, 2H, $\mathrm{C}H_2\text{-}\mathrm{CH_2\text{-}N}$), 1.73 (m, 2H, $\mathrm{C}H_2\text{-}\mathrm{CH_2\text{-}COO}$), 2.40 (m, 2H, $\mathrm{CH_2C}H_2\mathrm{COO}$), 3.24 (m, 2H, $\mathrm{CH_2\text{-}C}H_2\text{-}\mathrm{N}$), 3.30 (s, 9H, $\mathrm{C}H_3\text{-}\mathrm{N}$). ^{13}C NMR (75 MHz, $\mathrm{CDCl_3}$, δ, ppm): 178.9 (1C, $C\mathrm{OO}$), 66.6 (1C, $C\mathrm{H_2N}$), 53.0 (3C, $(C\mathrm{H_3})_3\mathrm{N}$), 38.1 (1C, $C\mathrm{H_2COO}$), 31.7 (2C, $C\mathrm{H_2(CH_2)_{13}N}$, $C\mathrm{H_2(CH_2)_5COO}$), 29.4 (7C, $(C\mathrm{H_2)_6(CH_2)_3N}$, $C\mathrm{H_2(CH_2)_2COO}$), 29.1 (2C, $(C\mathrm{H_2)_2(CH_2)_9N}$), 29.0 (4C, $(C\mathrm{H_2)_2(CH_2)_{11}N}$, $(C\mathrm{H_2)_2(CH_2)_3COO}$), 26.6 (1C, $C\mathrm{H_2CH_2N}$), 26.0 (1C, $C\mathrm{H_2CH_2COO}$), 23.0 (1C, $C\mathrm{H_2(CH_2)_2N}$), 22.5 (2C, $C\mathrm{H_2(CH_2)_{14}N}$, $C\mathrm{H_2(CH_2)_6COO}$), 13.9 (2C, $C\mathrm{H_3(CH_2)_{15}N}$, $C\mathrm{H_3(CH_2)_7COO}$). Anal. calc. for $\mathrm{C_{28}H_{59}NO_2}$: C, 76.12; H, 13.46; N, 3.17. Found: C, 75.94; H, 13.58; N, 3.00%.

2.4. Solubility

The solubility of the prepared ILs was determined according to Vogel`s Textbook of Practical Organic Chemistry [48]. Popular representative solvents were chosen and ranked in descending order of Snyder polarity index value (water - 9.0, methanol - 6.6, DMSO - 6.5, acetonitrile - 6.2, acetone - 5.1, ethyl acetate - 4.4, chloroform - 4.1, toluene - 2.3, hexane - 0.0). The term “complete solubility” refers to ILs, which were dissolved (0.1 g of IL) in 1 mL of solvent, while the term “limited solubility” means that the IL was dissolved in 3 mL of solvent. The term “insoluble” was used to describe no solubility of 0.1 g of IL in 3 mL of solvent. Tests were conducted at 20 °C under ambient pressure.

2.5. Thermal stability

Thermal transition temperatures were determined by DSC, with a Mettler Toledo Star^e DSC1 (Leicester, UK) unit, under nitrogen. ILs (between 5 and 15 mg) were placed in aluminum pans and heated from 25 to 120 °C at a heating rate of 10 °C/min, cooled with an intracooler at a cooling rate of 10 °C/min to -100 °C, then heated again to 120 °C. Thermogravimetric analysis was performed using a Mettler Toledo Star^e TGA/DSC1 unit (Leicester, UK), under nitrogen. ILs (between 2 and 10 mg) were placed in aluminum pans and heated from 30 to 450 °C at a heating rate of 10 °C/min.

2.6. Surface tension

The surface tension was determined using the pendant drop method. The measurements were carried out by the use of a DSA 100 analyzer (Krüss, Germany, accuracy ± 0.01 mN/m) at 25 °C (temperature controlled using a Fisherbrand FBH604 thermostatic bath - Fisher, with the accuracy of 0.1 °C). The principle of this method is to form an axisymmetric drop at the tip of a syringe needle. The image of the drop (3 mL) from a CCD camera was taken and digitized. The surface tension (in mN/m) is calculated by analyzing the profile of the drop according to the Laplace equation. The values of the critical micelle concentration (CMC) and the surface tension at the CMC (γCMC) were determined from the intersection of the two straight lines drawn in low and high concentration regions in surface tension curves (γCMC *vs* log C curves) using a linear regression analysis method. The basis for the determination of the contact angle is the image of the drop on the examined surface (paraffin). After determination of the actual drop shape and the contact line, the drop shape is adapted to fit a mathematical model used to calculate the contact angle. The most exact method to calculate this value is Young-Laplace fitting (sessile drop fitting). Complete drop contour is evaluated. After successful fitting of the Young-Laplace equation, the contact angle is determined as the slope of the contour line at the 3-phase contact point (solid-liquid and liquid-air). The measurements were carried out by the use of DSA 100 analyzer, Krüss.

2.7. Feeding deterrent activity

The bioassay experiments were conducted with *Tribolium confusum* Duv. (Larvae and adults), *Sitophilus granarius* L. (Adults), and *Trogoderma granarium* Ev. (Larvae). The insects were grown on a wheat grain or whole-wheat meal diet in laboratory colonies, which were maintained at 26 ± 1 °C and 60 ± 5% relative humidity. Choice and no-choice tests for insect-feeding were conducted following a previously described procedure [49]. Wheat wafers discs (1 cm in diameter, 1 mm thick) were saturated by dipping either in ethanol only (control) or in a solution of the studied ILs (1%) in ethanol to be tested. After evaporation of the solvent (30 min of air-drying) the wafers were weighted and offered to the insects in plastic boxes as the sole food source for 5 days. The feeding of insects was recorded under three sets of conditions: (1) on two control discs (*CC*), (2) on a choice between one treated disc (*T*) and one control disc (*C*; choice test), and (3) on two treated discs (*TT*; no-choice test). Each of the three experiments was repeated five times with 3 adults of *S. granarius*, 20 adults and 10 larvae of *T. confusum* and 10 larvae of *T. granarium.* The number of individual insects depended on the intensity of their food consumption. The adults used for experiments were unsexed, 7-10 days old, and the larvae were 5-30 days old. After 5 days the discs were weighted and the average weight of eaten food was calculated.

2.8. Antimicrobial activity

Antimicrobial activity was determined by the tube dilution method. A series of ammonium salts dilutions was prepared on Müller-Hinton broth medium (bacteria) or Sabouraud broth medium (fungi). Suspensions of the microorganisms, prepared from 24 h cultures of bacteria in the Müller-Hinton broth medium and from 48 h cultures in the Sabouraud agar medium for fungi, at a concentration of 10^6 cfu/mL, were added to each dilution in a 1+1 ratio. Growth (or lack of growth) of the microorganisms was determined visually after incubation for 24 h at 37 °C (bacteria) or 48 h at 28-30 °C (fungi).

Table 2. Solubility of prepared nonanoates *.

IL	Solvent								
	Water	**Methanol**	**DMSO**	**Acetonitrile**	**Acetone**	**Ethyl acetate**	**Chloroform**	**Toluene**	**Hexane**
1	±	+	-	-	-	-	±	±	-
2	±	+	+	±	±	±	+	±	-
3	+	+	+	±	±	±	+	±	-

* "+" - complete solubility, "±" - limited solubility, "-" – insoluble.

Table 3. Surface activity of synthesized ILs.

IL	CMC (mmol/L)	γ_{CMC} (mN/m)	π_{CMC} (mN/m)	pC_{20} -	Γ_{max} (μmol/m²)	A_{min} (10^{-19} m²)
1	0.245	21.86	50.82	4.96	1.99	8.31
2	0.513	26.63	45.99	4.18	2.55	6.51
3	0.246	28.01	44.51	4.08	4.57	3.63

The lowest concentration at which there was no visible growth (turbidity) was taken as the MIC. Then, one loopful from each tube was cultured on an agar medium with inactivates (0.3% lecithin, 3% polysorbate 80 and 0.1% cysteine L) and incubated for 48 h at 37 °C (bacteria) or for 5 days at 28-30 °C (fungi). The lowest concentration of the salt supporting no colony formation was defined as the MBC and MFC. The following microorganisms were used during the tests: standard strains representative of cocci - *Micrococcus luteus* ATCC 9341, *Staphylococcus aureus* ATCC 6538, *Staphylococcus epidermidis* ATCC 12228, *Enterococcus faecium* ATCC 49474; rods: *Moraxella catarrhalis* ATCC 25238, *Escherichia coli* NCTC 8196, *Bacillus subtilis* ATCC 6633, *Proteus vulgaris* NCTC 4635, and fungi - *Candida albicans* ATCC 10231, *Rhodotorula rubra* (Demml 1889, Lodder 1934). Standard strains were supplied by the National Collection of Type Cultures (NCTC) London and American Type Culture Collection (ATCC). *Rhodotorula rubra* was obtained from the Department of Pharmaceutical Bacteriology, K. Marcinkowski University of Medical Sciences, Poznan.

3. Results and discussion

Quaternary ammonium nonanoates were obtained with high yields, exceeding 90% (Table 1). Water content of the dried nonanoates was measured by Karl-Fischer method and found to be less than 300 ppm. The structures of synthesized quaternary ammonium nonanoates were confirmed with nuclear magnetic resonance (^{1}H and ^{13}C NMR) and elemental analysis (CHN).

Table 1 presents results of thermal gravimetric analysis (TGA) and differential scanning calorimetry (DSC). Differential scanning calorimetry revealed that all the synthesized compounds were ILs (T_m < 100 °C). ILs **1** and **2** were high viscosity liquids at room temperature, while IL **3** was a colorless solid. Determination of phase transition temperatures also allowed to distinguish ILs which occur in liquid state at room temperature. Strong determination of phase transition characteristics by ILs structure is visible. No glass transitions were observed for ILs **1** and **2**. IL **3** exhibited glass transition at the temperature of 20 °C. Crystallization and melting occurred in a wide range of temperatures. Lowest temperature values (-19 °C for crystallization and -6 °C for melting) were observed for IL **2** as this IL included a non-linear aromatic substituent in the structure of the cation. The presence of two saturated long-alkyl chains, able to bend and mutually interact in IL **1** resulted in a crystallization temperature at 18 °C and melting point at 33 °C. Highest values were determined for IL **3**, crystallization occurred at 93 °C, melting was observed at 96 °C.

Thermal stability curves revealed that the obtained ILs were thermally stable up to approx. 175 °C, when decomposition of IL **2** occurs. For IL **1** 5% weight loss was observed at 180 °C and decomposition of 50% of the sample occurred at 260 °C. IL **2** started to decompose at 175 °C and weight loss by 50% was noted at 243 °C. IL **3** was the most stable IL among the synthesized nonanoates. Degradation of 5% by weight occurred at 193 °C and 50% weight loss was observed at 231 °C. Generally, nonanoates with saturated alkyl chains in the structure of the cation were more stable than the IL with a benzyl substituent. The presence of a single alkyl chain promoted higher thermal stability. The obtained products were also stable in contact with air and soluble in polar solvents (Table 2).

Influence of the structure of ILs on their solubility is significant. ILs with more than one alkyl chain in the cation (**1** and **2**) were moderately soluble in water as the most polar solvent. Due to the ionic nature of the synthesized nonanoates, the ILs were insoluble in hexane. Solubility of IL **1** in solvents with a moderate polarity index (C-F) decreased and then returned to its previous level in solvents with lower polarity (G,H). Such behavior is most likely caused by presence of two long-chain alkyl substituents in cation and their interactions with particles of solvents.

Surface activity parameters: critical micelle concentration (CMC), surface tension at CMC (γ_{CMC}), effectiveness of surface tension reduction (π_{CMC}), efficiency of surface adsorption on an air-water interface (pC_{20}), maximum surface excess concentration (Γ_{max}) and surface area occupied by IL molecules (A_{min}) were characterized (Table 3).

As shown in Table 3, best results were achieved for IL **1** as well as **3**. This is most likely associated with the linear structure of alkyl substituents in the particle. IL **2** presented higher CMC value due to possible interactions between solvent and free electrons of the aromatic ring. The effectiveness of surface tension reduction, also called surface pressure at the saturated air/solution interphase, and the adsorption efficiency pC_{20} are also important surface parameters. Adsorption efficiency is defined by using the Equation (1).

$$pC_{20} = -\log C_{20} \tag{1}$$

where C_{20} is the molality of the compound which leads to a reduction of the surface tension of the solvent by 20 mN/m.

IL **1** reduced the surface tension of water to 21.86 mN/m which is a very good result. On the other hand, the remaining two nonanoates reduced the surface tension value to 26-28 mN/m which is characteristic for cationic surface active compounds [50].

The higher the value of pC_{20} is associated with, the higher adsorption efficiency of the compound. The values of π_{CMC} and pC_{20} obtained for the investigated ILs are also listed in Table 3. The relations between the surface tension values for aqueous solutions of the synthesized ILs and the log of concentration were determined (Figure 1).

It can be observed that the surface tension of the aqueous solutions of the synthesized ILs showed a progressive decrease with increasing concentration and remained constant above the CMC.

Contact angle values of the prepared nonanoates were determined based on drop shape analysis on the examined surface - paraffin (Figure 2).

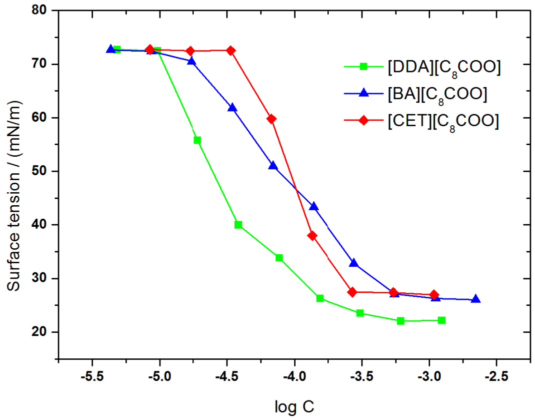


Figure 1. Surface tension of the synthesized ILs as function of concentration at 25 °C.

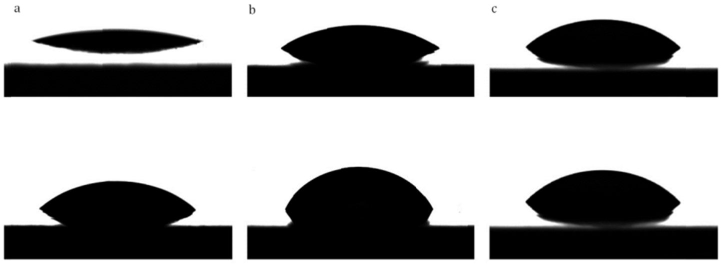


Figure 2. Drop shapes of the prepared ILs (upper) on paraffin base compared to chlorides (lower): a) **1**, b) **2**, c) **3**.

Presence of the pelargonate anion in ILs caused a rapid decrease of contact angle values. For didecyldimethyl ammonium salts, the contact angle value was lowered from 42.5 ° for chloride to 10.6 ° for IL **1**. Benzalkonium salts exhibited the highest difference between CA values - 68.6 ° for chloride and 34.5 ° for pelargonate. The smallest difference was observed in case of hexadecyltrimethylammonium salts - 72.3 ° for chloride and 44.8 ° for IL **3**.

The synthesized ILs were tested against *Sitophilus granarius*, *Tribolium confusum* (both adult specimen and larvae) and *Trogoderma granarium* (larvae). Feeding deterrent activity was estimated based on the amount of food consumed. Values of coefficients A (absolute coefficient of deterrence) and R (relative coefficient of deterrence) were calculated as follows:

$$A = \frac{CC-TT}{CC+TT} \times 100 \quad (2)$$

$$R = \frac{C-T}{C+T} \times 100 \quad (3)$$

where *CC* was the average weight of the food consumed in the control, *TT* was the average weight of the food consumed in the no-choice test and *C* and *T* expressed the average weights of the food consumed in the choice test. The sum of these two coefficients was used to evaluate the total coefficient of deterrence (T), based on the following criteria: 200-151 very good, 150-101 good, 100-50 medium, < 50 weak.

IL **1** was the most efficient feeding deterrent - values of all parameters reached or were close to maximum (Figure 3). IL **1** was effective in both choice and no-choice test. The very low consumption in the no-choice test shows very good deterrent activity of this substance, since the insects preferred to starve than eat treated wafers. The *S. granarius* beetles had completely ignored the treated wafers and their total deterrent activity was 200. The larvae of *T. confusum* (T-198) and *T. granarium* (T-198) were characterized by a little lower level of T. The beetles (adults) of *T. confusum* (T-183) were the most resistant organisms to the tested IL. Deterrent activity of IL **1** was very good to all test insects. This IL has an even stronger deterrence effect compared to azadirachtin in case of *S. granarius* beetles and larvae of *T. confusum*. Feeding deterrence of IL **2** was lower than IL **1**, however the values of total deterrence coefficient oscillated above 150, making the obtained IL a very good deterrent (Figure 4).

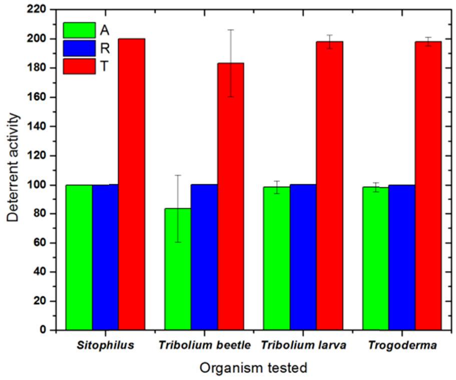


Figure 3. Deterrent activity of IL **1**.

The prepared IL **2** was most efficient towards beetles of *T. confusum* (T-181) and larvae of *T. granarium* (T-184). The larvae of *T. confusum* exhibited a higher tolerance to the tested IL (T-159). The T index value was lower only in the case of *S. granarius* beetles and stayed within a range good coefficient of deterrence (T-141). No-choice test revealed that the insects consumed food containing the tested compound, but in small amounts. Efficacy of IL **2** increased during choice test, where insects consumed the food from the treated wafers. Compared with azadirachtin IL **2** exhibited a weaker deterrent activity for all tested insects.

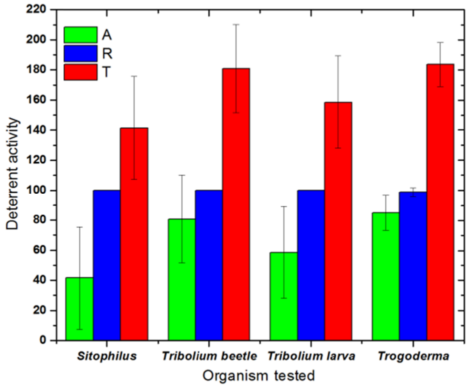


Figure 4. Feeding deterrence activity of IL **2**.

Feeding deterrence of IL **3** is presented in Figure 5. This IL was characterized by the lowest deterrence activity among the tested ILs. All ILs can be described as very good or good deterrents. The influence of long alkyl chain on the deterrent activity is strong. Correlation between feeding deterrence activity and the structure of synthesized ILs was determined (Figure 6).

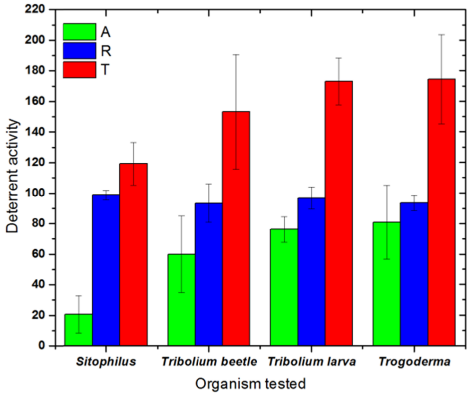


Figure 5. Deterrent activity of IL **3**.

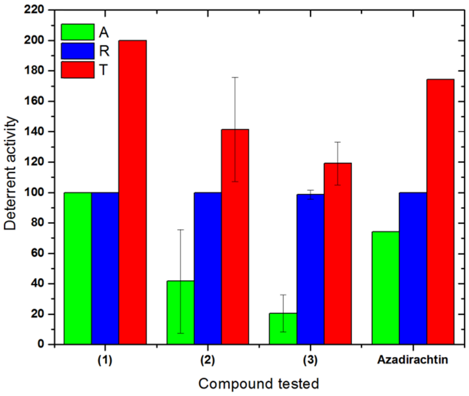


Figure 6. Deterrent activity of synthesized nonanoates and azadirachtin [51] towards *S. granarius*.

IL **1** with two long alkyl chains in the structure of the cation was most effective towards *S. granarius*, while IL **3**, with only a single long-chain alkyl substituent, exhibited the lowest activity. A similar trend was also observed for other tested organisms. Anti-feedant properties of azadirachtin towards the tested organisms have been described previously [51]. When compared to azadirachtin, the best anti-feedant properties were obtained for IL **1**. The total coefficient values (T) for this IL exceeded the results of azadirachtin for three out of four tested organisms.

Since the chemical structures of the obtained nonanoates determine both their surface properties and feeding deterrence activity, an attempt to describe the dependence between these two parameters was conducted. The relations between the value of pC_{20} parameter, described as negative logarithm of the surfactant concentration in the bulk phase required to reduce the surface tension of water by 20 mN/m, and feeding deterrence of the obtained ILs towards *S. granarius*, *T. confusum* and *T. granarium* are presented in Figure 7.

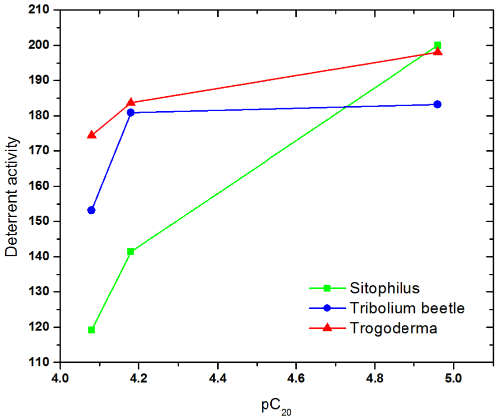


Figure 7. Correlation between surface activity and feeding deterrence properties of the synthesized nonanoates.

The curves reflect the dependence between antifeedants properties and surface activity of the synthesized nonanoates. The highest surface activity of IL **1** matches with the highest results obtained during the feeding deterrence test. It can be observed that the lower pC_{20} values in case of IL **2** and **3** correspond to a decreased effectiveness of the synthesized ILs as feeding deterrents The correlation between surface activity and antifeedants properties has been examined for the first time.

The antimicrobial activity of quaternary ammonium chlorides ([QAC][Cl]) and their widespread use in disinfectant formulations were the basis for conducting appropriate tests for the synthesized nonanoates. Antimicrobial properties were investigated against bacteria and fungi by determining the MIC/MBC and MIC/MFC values. Results show that the tested ILs were effective towards most of the tested microorganisms (Table 4).

The calculated values differed from 8 to 46 ppm only in the case of *P. vulgaris* and *C. albicans*. Activity of the obtained nonanoates remained at the same level as their precursors - the MIC/MBC and MIC/MFC values did not change significantly. Additionally, IL **1** can be indicated as the most effective antimicrobial agent among studied ILs.

4. Conclusions

This study focused on the synthesis of quaternary ammonium nonanoate-based ILs and subsequent analysis of their properties. The employed synthesis method allowed to obtain compounds with high yields and high purity, as confirmed by NMR and elemental analyzes.

Table 4. Antimicrobial activity of synthesized ILs and their precursors.

Species	**Activity** [a]	**[QAC][C_8COO]**			**[QAC][Cl]**		
		[DDA] [b]	**[BA]** [c]	**[CET]** [d]	**[DDA]** [b]	**[BA]** [c]	**[CET]** [d]
M. luteus	MIC	0.1	0.2	0.2	0.1	0.1	0.5
	MBC	0.1	0.5	0.5	0.1	0.1	1.0
S. aureus	MIC	0.1	1.0	0.5	0.1	0.2	1.0
	MBC	1.0	1.0	2.0	0.2	2.0	1.0
S. epidermidis	MIC	0.1	2.0	0.2	0.1	2.0	0.5
	MBC	0.2	2.0	0.5	0.2	2.0	2.0
E. faecium	MIC	0.2	2.0	4.0	0.1	1.0	1.0
	MBC	0.2	2.0	8.0	0.2	1.0	2.0
M. catarrhalis	MIC	0.1	2.0	0.1	0.1	1.0	1.0
	MBC	1.0	4.0	0.5	0.2	2.0	1.0
E. coli	MIC	0.1	0.5	0.5	0.1	1.0	0.5
	MBC	0.1	2.0	1.0	0.2	2.0	4.0
P. vulgaris	MIC	16.0	31.0	62.0	4.0	8.0	31.0
	MBC	16.0	62.0	62.0	8.0	16.0	62.0
B. subtilis	MIC	0.1	0.5	0.2	1.0	1.0	1.0
	MBC	0.1	0.5	0.2	2.0	1.0	2.0
C. albicans	MIC	4.0	2.0	8.0	4.0	2.0	1.0
	MFC	16.0	8.0	8.0	4.0	4.0	1.0
R. rubra	MIC	4.0	2.0	31.0	4.0	2.0	0.5
	MFC	4.0	8.0	31.0	4.0	2.0	0.5

[a] Unit in ppm.

[b] Didecyldimethylammonium cation.

[c] Benzalkonium cation.

[d] Hexadecyltrimethylammonium cation.

It was established, that the structure of the cation had a notable influence on the physicochemical characteristics (thermal stability and solubility), surface activity and biological properties (feeding deterrence and antimicrobial activity) of the studied ILs.

The conducted tests confirmed that each of the obtained ILs was characterized by good surface and biological activity. Among the studied ILs, the most promising results were exhibited by didecyldimethylammonium nonanoate. This IL was most efficient in terms of surface active properties (surface tension of water reduced to 21.86 mN/m) as well as feeding deterrence (higher activity compared to the standard, azadirachtin, for three out of four tested organisms). The obtained results indicate that the specific shifts in properties of the obtained ILs may be mainly attributed to the structure of the cation. The presence of two long alkyl chain substituents in didecyldimethylammonium nonanoate contributed to beneficial changes. On the other hand, no notable influence of the anion was observed, since exchange of the chloride anion to nonanoate did not significantly affect the antimicrobial properties of the synthesized ILs.

Furthermore, an attempt to correlate the feeding deterrent activity of the obtained ILs with their surface active properties was conducted. It was observed, that an increase of the feeding deterrent activity is positively correlated with the efficiency of surface adsorption on an air-water interface (pC_{20}). To the best of our knowledge, this is the first report regarding this type of correlation.

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