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Synthesis and characterization of herbicidal ionic liquids based on (4-chloro-2-methylphenoxy)acetate and phenoxyethylammonium

Kamil Ciarka[1,2] · Radoslaw Olszewski[1,2] · Tadeusz Praczyk[3] · Juliusz Pernak[4]

Abstract

Ten ionic liquids containing the (4-chloro-2-methylphenoxy)acetate (MCPA) anion and domiphen derived phenoxyethyl-ammonium cation were synthesized. The obtained compounds differed in terms of the substitution of the phenoxyethylam-monium group in the ring (the presence of a methyl group in the *meta* or *para* positions and the presence of chlorine in the *para* position) as well as the length of the alkyl chain (from hexyl to tetradecyl). The basic physicochemical properties of the obtained ionic liquids (solubility and thermal stability) were characterized and their structures were confirmed. The herbicidal activity of the compounds was tested under greenhouse conditions using cornflower (*Centaurea cyanus* L.) as the test plant.

Keywords Ionic liquids · Herbicides · Phenoxyethylammonium · MCPA · Domiphen

Introduction

Ionic liquids (ILs), defined as ionic compounds with a melting point below 100 °C (Visser et al. 2012; Wasserscheid and Welton 2002), are still the subject of intense interest and research due to their unique properties and the vast amount of cation–anion combinations, which is estimated at the level of 10^{18} Holbrey and Seddon (1999). New types of ILs are described on a regular basis as a result of their recognized properties and the search for potential applications. Initially, they were an alternative to toxic solvents, and were used in chemical synthesis, extraction (Wang et al. 2020), catalysis (Dyson and Geldbach 2005) and electrochemical processes (Wojciechowski et al. 2017). Important research concerns the use of ILs as a solvent for biopolymers, e.g. in the process of dissolving cellulose or extracting lignin from biomass, and the processes of its transformation into aromatic compounds (Chatel and Rogers 2014; Swatloski et al. 2002; Ohno and Fukaya 2009).

The appropriate selection of cations and anions during the design of ILs determines their properties. A convenient division of ILs is based on the idea of three generations (Hough et al. 2007; Smiglak et al. 2014; Zając et al. 2018). The 1st generation is focused on the physical quantities, the 2nd generation is focused on the physical and chemical parameters, and the 3rd generation is the combination of 1st and 2nd generations with an extension to the biological properties. Examples of the 3rd generation include pharmaceuticals, plant protection products and antibiotics, the bioavailabilities of which were improved by their conversion into ILs (Bica and Rogers 2010).

The transformation of carboxylic acids (cinnamic, benzoic, salicylic, nicotinic, 2-methylphenoxyacetic, succinic, malonic, oxalic, malic and citric) and phenoxyacetic acids derivatives into ionic liquids is known (Kondratenko et al. 2020; Voronkov et al. 2014). Triethanolammonium salt of 2-methylphenoxyacetic acid (creasin, trecrezan) was introduced with unique physiological properties, in particular efficient adaptogenic and immunostimulatory effects were exhibited. It is opened wide prospects for its application in medicine and agriculture. A chloro-substituted analog of creasin, tris(2-hydroxyethyl)ammonium (4-chloro-2-methylphenoxy)acetate (chlorocreasin) turned out to be even more efficient as physiologically active substance and

✉ Kamil Ciarka
  kamil.ciarka@adob.com.pl

1   Faculty of Chemistry, Adam Mickiewicz University, ul.
    Uniwersytetu Poznanskiego 8, 61-614 Poznan, Poland

2   PPC ADOB, ul. Kolodzieja 11, 61-070 Poznan, Poland

3   Institute of Plant Protection–National Research Institute,
    ul. Wegorka 20, 60-318 Poznan, Poland

4   Department of Chemical Technology, Poznan University
    of Technology, ul. Berdychowo 4, 60-965 Poznan, Poland

it exhibited pronounced antitumor activity (Voronkov and Rasulov 2007).

In 2011, it was proposed to transform known herbicides into herbicidal ionic liquids (HILs), which results in a decrease in the volatility of the herbicide, an increase in the effectiveness of its action and, at the same time, allows for regulation of the water solubility and toxicity (Pernak et al. 2011). This approach has been demonstrated by the transformation of popular herbicides (such as 2,4-D (Junfan et al. 2018), MCPA (Pernak et al. 2011), glyphosate (Marcinkowska and Łacka 2019), metsulfuron (Pernak et al. 2015), dicamba (Syguda et al. 2020) and pelargonic acid (Turguła et al. 2020)) into HILs.

The (4-chloro-2-methylphenoxy) acetic acid (MCPA) herbicide belongs to the group of synthetic auxins, also known as growth regulators, due to its mechanism of action. The same group of agents also includes herbicides such as dicamba, mecoprop, and 2, 4-D. They are most often used in the herbicidal protection of crops to combat many species of dicotyledonous weeds (Zimdahl 2007).

MCPA in commercial products is most often applied in the form of sodium–potassium or dimethylamine salts (Tomlin 2009). Numerous studies have been conducted regarding the impact of pesticides on the natural environment (Syguda et al. 2018; Gang et al. 2020; Parus et al. 2019; Pęziak-Kowalska et al. 2019), and hence, special attention is paid to the development of new formulations that would allow for the reduction in the amount of active substances applied while maintaining the same level of crop protection (Niemczak et al. 2020; Ten et al. 2020; Giszter et al. 2016). Directive 2009/128/EC of the European Parliament and the Council from the 21st of October 2009 established a framework for community action for the sustainable use of pesticides and obliges all professional users to apply integrated pest management, which emphasizes the production of healthy crops with minimal disruption to the functioning of the agricultural ecosystem. According to this idea, plant protection products placed on the market should have a reduced risk of a negative impact on human health and the environment.

One of the methods to improve the ecotoxicological properties of plant protection products could be the transformation of active substances into ionic liquids. The appropriate design of HILs allows products to be obtained with an enhanced spectrum of action and, at the same time, a lower impact on the natural environment. A review was recently published on the synthesis, toxicity, biodegradation and efficacy studies of HILs (Wilms et al. 2020). Bearing in mind that about 30% of pesticides applied on leaves go directly to the soil, biodegradation of plant protection products becomes an important topic in the discussion on the use of herbicidal liquids in agriculture. The agricultural pesticides that applied to the land surface travel long distances and can move downward until reaching the water table surface at detectable concentrations, reaching aquatic environments at significantly longer distances. The coefficient of absorption and degradation of active substances depends on soil parameters: pH, organic matter content and air humidity. Also the degradation of phenoxy acids also depends on the amount of bacteria present in the soil (Paszko et al. 2016). The high affinity of the positive charge contained in quaternary salts can cause the binding of cations with the organic substances present in the soil. Additionally, it is documented that the influence of the length of the alkyl substituent and the presence of an aromatic ring in ammonium salts adversely affects the biodegradation process (Hora et al. 2020).

Domiphen bromide is an example of a commercial use of this type of compound. This compound exhibits antibacterial and antiseptic properties and is used in the pharmaceutical industry (Yan et al. 2017). Additionally, domiphen mandelate and prolinate have been described as antimicrobial and antifungal ILs and employed for the asymmetric Michael addition (Cybulski et al. 2011).

The aim of this study is the synthesis of ILs with ion acetate of MCPA as the anion and phenoxyamine derivatives as the ammonium cations that may have a dual aspect of action, herbicidal and bactericidal, and which can become an alternative to the commercially used volatile MCPA esters.

Experimental

Materials

Sodium hydroxide (≥ 97.0%), phenol (≥ 99%), 4-chlorophenol (≥ 99%), 4-chloro-3-methylphenol (99%), *p*-cresol (99%), 2-chloro-*N*,*N*-dimethylethylamine hydrochloride (99%), 3-dimethylamino-1-propyl chloride (96%), 1-bromohexane (98%), 1-bromooctane (99%), 1-bromodecane (98%), 1-bromododecane (97%), 1-bromotetradecane (97%), dimethyl sulfoxide (≥ 99.9%) and domiphen bromide (97%) were purchased from Sigma Aldrich. Solvents: 2-propanol (99.9%), methanol (≥ 99.9%), acetonitrile (≥ 99.9%), acetone (≥ 99.5%), ethyl acetate (≥ 99.5%), chloroform (≥ 99.8%), toluene (≥ 99.5%), hexane (≥ 99%) were purchased from Sigma Aldrich, whereas (4-chloro-2-methylphenoxy)acetic acid (97%) was obtained from CIECH Sarzyna (Nowa Sarzyna, Poland). Anion Exchange Resin AmberTec® UP550 OH was purchased from Merck. Deionized water with conductivity < 0.1 μS cm^{-1} obtained using the HLP Smart 1000 demineralizer (Hydrolab, Poland) was used for synthesis and measurements. All reagents and solvents were used without further purification.

General

The ^1H and ^{13}C NMR analyses were performed using a BRUKER ASCEND™ 400 MHz NANOBAY at 400 MHz and 100 MHz, respectively. Tetramethylsilane (TMS) was used as a standard and deuterated methanol (CD_3OD) was used as the solvent. The melting point was measured using a Buchi Melting Point B-540. LC–MS/MS analyses were conducted on Shimadzu Nexera X2 LCMS-8040 with SPD-M30A DAD detector, LC-30AD pump and SIL-30AC autosampler. Eluent was 0.1 mL/min gradient flow of 1:1 mixture of 0.1% TFA in water with acetonitrile. Volume of injection was equal to 1 µl. FT-IR analyses were conducted on Thermo Nicolet FT-IR iS10 spectrometer in range of 650–4000 cm^{-1} at resolution of 1 cm^{-1}.

Synthesis of phenoxyamines

Initially, 0.1 mol of the appropriate phenol, 0.2 mol of sodium hydroxide and 30 mL of isopropanol were placed in a reaction vessel equipped with a magnetic stirrer, a thermometer and a reflux condenser. The mixture was heated to 50 °C. Then, a solution of 0.11 mol of the appropriate amine in 20 mL of water was added dropwise over 10 min. After stirring for 5 h, isopropanol was evaporated and the remaining aqueous solution was cooled and extracted three times with chloroform. The combined organic layers were washed twice with water and then chloroform was evaporated. The product was dried at 40 °C under reduced pressure.

Quaternization reaction

To conduct the quaternization reaction, 0.1 mol of the appropriate amine and 0.11 mol of the appropriate bromoalkane were placed in a reaction vessel equipped with a magnetic stirrer, thermometer and reflux condenser. The reactants were dissolved in 50 mL of acetonitrile, and then, the mixture was heated to 60 °C and stirred for 20 h. The product appears as a white precipitate. It was cooled to − 10 °C, and then, the precipitate was filtered off and washed with hexane. The product was dried at 40 °C under reduced pressure.

Ion exchange

To conduct the ion exchange, 0.1 mol of the appropriate bromide and 100 mL of methanol were placed in a reaction vessel equipped with a magnetic stirrer. After dissolution, 50 mL of ion exchange resin was added to the mixture. After stirring for an hour, the resin was filtered off. The obtained

hydroxide solution was used directly in the next synthesis step.

Synthesis of ILs

A methanolic solution of 0.1 mol of the appropriate hydroxide was placed in a reaction vessel equipped with a magnetic stirrer. Then, a solution of 0.1 mol of (4-chloro-2-methylphenoxy)acetic acid in 50 mL of methanol was added. The neutralization reaction was carried out at 20 °C for 1 h. After evaporating the solvent, the product was dried at 40 °C under reduced pressure.

Solubility assay

The solubility of the obtained ILs was tested based on the Vogel Textbook of Practical Organic Chemistry (Furniss et al. 1989). Ten solvents were selected for testing: water, methanol, DMSO, acetonitrile, acetone, isopropanol, ethyl acetate, chloroform, toluene and hexane. The test allowed to classify the obtained ILs into one of the three groups for each solvent. The first group was defined as "good solubility" (+) which means that 0.1 g of the compound is dissolved in 1 mL of the solvent. The second group, defined as "limited solubility" (±), was used when 0.1 g of the compound is dissolved in 2 or 3 mL of the solvent. The last group labelled "poor solubility" (−) was employed when 0.1 g of the compound was not dissolved in 3 mL of the solvent. The tests were carried out at 25 °C and atmospheric pressure.

Thermal analysis

The thermal transformation temperatures of the obtained salts were determined by DSC using a Mettler Toledo Stare TGA/DSCl apparatus (Leicester, UK). During the analysis of the Phase Conversion Temperature values, samples between 5 and 15 mg were placed in aluminium pans, heated from 25 to 120 °C at a heating rate of 10 °C per min and cooled using an intracooler at a cooling rate of 10 °C per min to − 100 °C. During the analysis of the decomposition temperature values, samples between 2 and 10 mg were placed in aluminium pans and heated from 30 to 450 °C at a heating rate of 10 °C per min. Nitrogen was used as the carrier gas.

Herbicidal activity

The herbicidal activity of the obtained ILs was tested under greenhouse conditions. Cornflower (*Centaurea cyanus* L. 1753) was used as the test plant. All salts were dissolved in a mixture of water and ethanol (0.4:0.6 v/v). The commercial product Chwastox Extra 300 SL (300 g of MCPA in the form of sodium and potassium salts per 1 L of solution) was used as a reference substance. Seeds
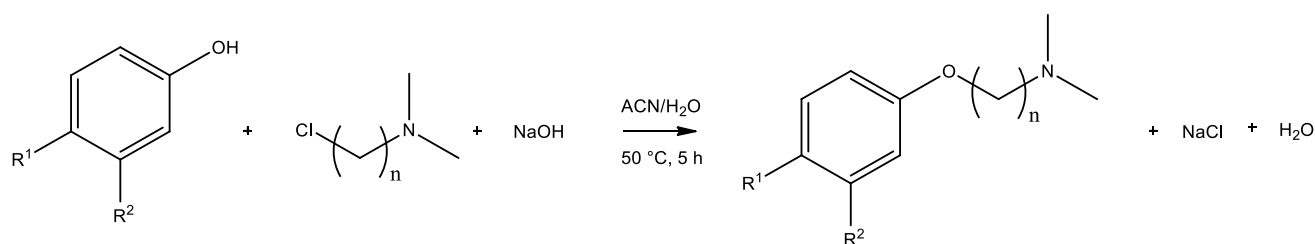
Scheme 1 Synthesis of phenoxyamines (**1–5**). For R^1, R^2, n see Table 1

Table 1 Synthesized phenoxyamines (**1–5**)

Amine	R^1	R^2	n	Yield (%)
1	H	H	2	63
2	Cl	CH_3	2	78
3	CH_3	H	2	72
4	Cl	H	2	75
5	CH_3	H	3	61

were sown in a pot (0.5 L) and kept under greenhouse conditions at 20 °C, 60% humidity and a 16/8 h (day/night) photoperiod. Cornflower plants were treated with herbicides at the 4–6 leaf stage of development. The herbicide application was performed using a cabin sprayer (APORO, Poznań, Poland) with a movable spraying beam equipped with a TeeJet 110/02 flat fan sprayer (TeeJet Technologies, Wheaton, IL, USA) delivering 200 L of herbicide solution per 1 ha of cultivation at the pressure 0.2 MPa. The distance between the sprayer and the plants was equal to 40 cm. The experiment was performed in four replications. After two weeks, the plants were cut at soil level and weighed (accuracy 0.01 g). Fresh biomass reduction for the individual variants was compared to the control crop to which no herbicide formulation was applied. The synthesized ionic liquids containing ion acetate of MCPA as the anion and the control preparation Chwastox 300 SL were applied at a dose of 400 g of MCPA per hectare, calculated based on the active substance.

Results and discussion

The Williamson reaction between sodium phenate, containing a chlorine atom or a methyl substituent in the ring, and amines yielded phenoxyethyl-*N,N*-dimethylamine and phenoxypropyl-*N,N*-dimethylamine (Scheme 1).

The obtained phenoxyamines were purified from the excess of unreacted reagents by extraction with an organic solvent. The synthesized compounds are listed in Table 1. The reaction yields ranged between 61 and 78%. The structures of the obtained amines were confirmed by ^{1}H and ^{13}C NMR.

Spectra of compounds **1–5** are included in ESI (Figs. 1–10). One of synthesized phenoxy amines is *N,N*-dimethyl-2-(4-methylphenoxy)ethylamine (**3**). In this molecule, protons bound to the methyl group in ring exhibit chemical shift $\delta = 2.06$ and protons from methyl groups bonded with nitrogen have chemical shift $\delta = 2.10$. Ethylene bridge forms two triplet signals of $\delta = 2.49$ for protons from carbon bound to nitrogen, and $\delta = 3.81$ for protons from carbon bound to oxygen. Signals of $\delta = 6.64$ and $\delta = 6.86$ correspond to protons from phenoxy ring. Their symmetric appearance is result of symmetric substitution of the phenyl ring.

The Menshutkin reaction between phenoxyethyl-*N,N*-dimethylamines and 1-bromoalkane (Scheme 2) resulted in the formation of crystalline quaternary ammonium bromides with a melting point from 39 for **8** to 150 °C for **10**, which are summarized in Table 2. Due to their melting point being lower than 100 °C, ammonium bromides **6**,
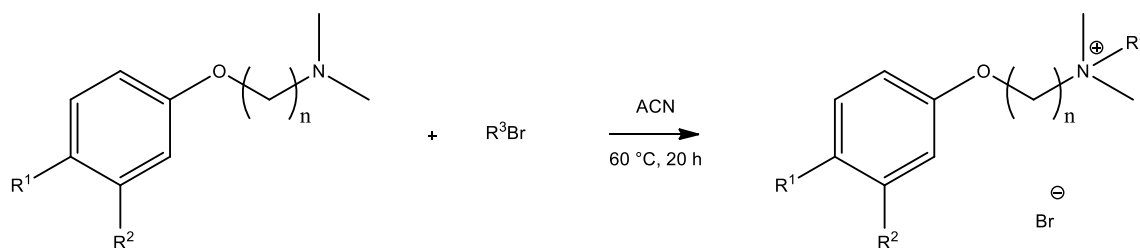
Scheme 2 Synthesis of the quaternary ammonium bromides (**6–14**). For R^1, R^2, R^3, n see Table 2

Table 2 Synthesized quaternary ammonium bromides (**6**–**14**)

Bromide	R^1	R^2	R^3	n	Melting point (°C)	Yield (%)
6	H	H	C_6H_{13}	2	63–65	93
7	Cl	CH_3	C_6H_{13}	2	131–133	87
8	CH_3	H	C_6H_{13}	2	38–40	82
9	Cl	H	C_6H_{13}	2	97–99	83
10	CH_3	H	C_8H_{17}	2	149–151	82
11	CH_3	H	$C_{10}H_{21}$	2	119–121	83
12	CH_3	H	$C_{12}H_{25}$	2	74–76	80
13	CH_3	H	$C_{14}H_{29}$	2	75–77	82
14	CH_3	H	C_6H_{13}	3	43–45	81

8, **9** and **12** can be recognized as ionic liquids. All compounds **6**–**14** appear in form of white solid.

The reaction yield exceeded 80%. The structures of the new bromides were confirmed by ^{1}H and ^{13}C NMR. The spectra are summarized in the ESI (Figs. 11–28).

Reaction of **3** with 1-bromohexane results in *N,N*-dimethyl-*N*-hexyl-*N*-(4-methylphenoxy)ethylammonium bromide (**8**). Protons from alkyl chain are represented by 4 signals: triplet at $\delta = 1.02$ for protons from terminal methyl group, multiplet at $\delta = 1.48$ represents 6 protons from chain carbons C2–C4, multiplet at $\delta = 1.93$ is associated with protons from carbon C5 and multiplet at $\delta = 3.61$ is representing protons from carbon bonded to nitrogen. Methyl groups are represented by singlets at $\delta = 2.36$ for protons from methyl group in ring, and $\delta = 3.35$ for methyl groups bonded to nitrogen. Two triplets at $\delta = 3.97$ and $\delta = 4.54$ represent protons from ethylene group, from carbon bonded to nitrogen and from carbon bonded to oxygen, respectively. Symmetry of signals from ring protons at $\delta = 7.02$ and $\delta = 7.20$ was preserved compared to amine **3**.

The synthesized bromides were converted into hydroxides using an ion-exchange resin according to the scheme presented in Scheme 3.

The ion exchange efficiency was equal to 98–99%. The last stage of the synthesis was the neutralization reaction of the synthesized hydroxides with (4-chloro-2-methylphenoxy)acetic acid (MCPA) (Scheme 4).

The reaction was carried out in methanol. The obtained products with high yields ranging from 93 to 99% are summarized in Table 3. The compounds are new high viscosity quaternary ammonium salts which can be classified as room-temperature ILs. Their structures were determined by ^{1}H and ^{13}C NMR (Figs. 29–48 in the ESI), LC–MS/MS (Figs. 49–68 in the ESI) and FT-IR spectra (Figs. 69–78 in the ESI).

Final IL based on ammonium bromide **8** is *N,N*-dimethyl-*N*-hexyl-*N*-(4-methylphenoxy)ethylammonium (4-chloro-2-methylphenoxy)acetate (**18**). ^{1}H NMR spectrum shows signals both from the ion acetate of MCPA and ammonium cation. Signals at $\delta = 0.66$, $\delta = 1.09$, $\delta = 1.50$ and $\delta = 3.13$ represent protons from alkyl chain carbons C6, C2–C4, C5 and C1, respectively. Protons from four methyl groups present in this IL are represented by signals at $\delta = 1.96$ and $\delta = 1.99$ for ring methyl groups, and $\delta = 2.89$ for 6 protons from 2 methyl groups connected to nitrogen. Singlet at $\delta = 4.18$ is associated with protons from methylene group in ion acetate of MCPA moiety. Ethylene bridge proton signals have chemical shift of $\delta = 3.50$ and $\delta = 4.50$ for protons from carbon bonded to nitrogen and oxygen, respectively.

Positive ionization MS spectrum of **18** confirms molecular mass of the ammonium cation. On the basis of selected peaks from fragmentation spectrum structure of precursor ion can be determined. Signal of $m/z = 130.00$ represents *N,N*-dimethyl-*N*-hexylaminium ion. Signal of $m/z = 135.20$ represents (4-methylphenoxy)ethylium ion. Signal of
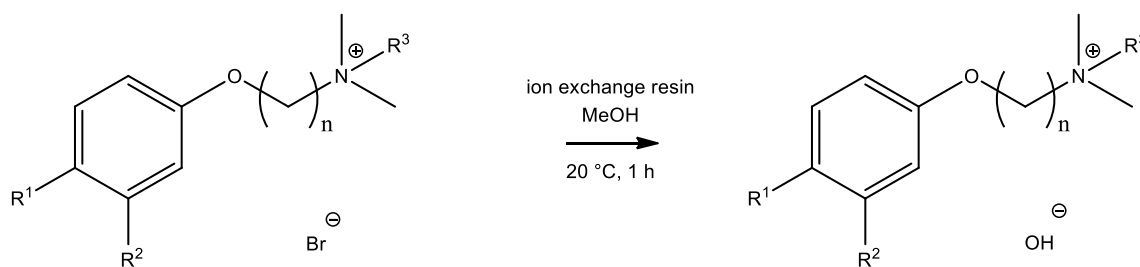
Scheme 3 Synthesis of hydroxides on ion exchange resin. For R^1, R^2, R^3, n see Table 2

$m/z = 179.90$ represents *N,N*-dimethyl-2-(4-methylphenoxy) ethanaminium ion. Presence of these fragmentation ions confirms structure of cation moiety of **18**.

The solubility of the synthesized ILs was determined according to the methodology presented by Vogel. The obtained results (Table 4) indicate that all compounds are

soluble in methanol and chloroform, and insoluble in water and hexane. The tested ILs exhibit good or limited solubility in DMSO, acetonitrile, acetone and isopropanol. In the case of ethyl acetate and toluene, all ILs are characterized by good solubility with the exception of **17**, **19** and **20**, which are insoluble therein.
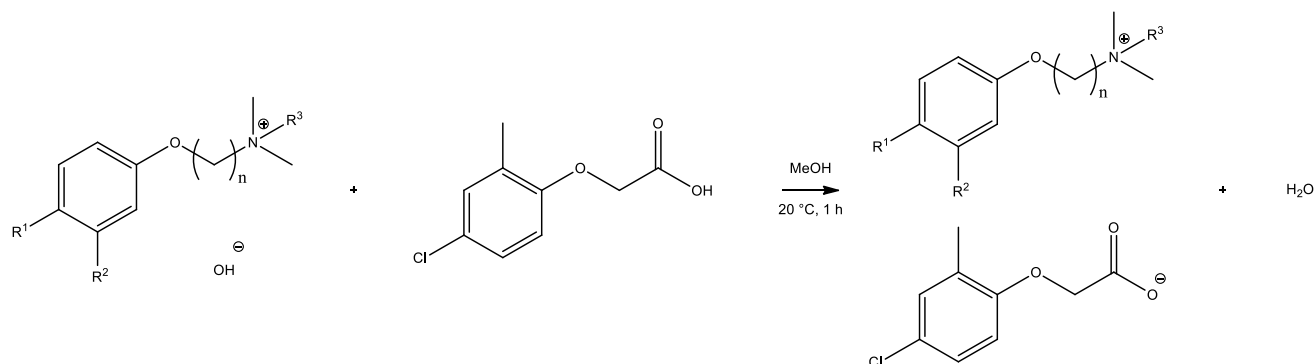
Scheme 4 Synthesis of ILs (**15–24**). For R^1, R^2, R^3, *n* see Table 3

Table 3 Synthesized ILs (**15–24**)

IL	R^1	R^2	R^3	*n*	Yield (%)	State at 20 °C
15	H	H	C_6H_{13}	2	97	liquid
16	Cl	CH_3	C_6H_{13}	2	99	liquid
17	Cl	H	C_6H_{13}	2	99	liquid
18	CH_3	H	C_6H_{13}	2	96	liquid
19	CH_3	H	C_8H_{17}	2	96	liquid
20	CH_3	H	$C_{10}H_{21}$	2	94	liquid
21	CH_3	H	$C_{12}H_{25}$	2	95	liquid
22	CH_3	H	$C_{14}H_{29}$	2	94	liquid
23	CH_3	H	C_6H_{13}	3	93	liquid
24	H	H	$C_{12}H_{25}$	2	98	liquid

Table 4 Solubility of prepared ILs (**15–24**) at 25 °C[b]

IL	Water 9.0[a]	Methanol 6.6	DMSO 6.5	Acetonitrile 6.2	Acetone 5.1	Isopropanol 4.3	Ethyl acetate 4.3	Chloroform 4.1	Toluene 2.3	Hexane 0
15	– [b]	+	+	+	+	+	+	+	+	–
16	–	+	+	+	+	+	+	+	+	–
17	–	+	+	+	±	±	–	+	–	–
18	–	+	+	+	+	+	+	+	+	–
19	–	+	±	±	±	±	–	+	–	–
20	–	+	±	+	±	±	–	+	–	–
21	–	+	+	+	+	+	+	+	+	–
22	–	+	+	+	+	+	+	+	+	–
23	–	+	+	+	+	+	+	+	+	–
24	–	+	+	+	+	+	±	+	+	–

[a] Snyder polarity index [b] + high solubility (more than 0.1 g can be dissolved in 1 mL of solvent), ± moderate solubility (0.1 g can be dissolved in 2–3 mL of solvent), – low solubility (less than 0.1 g can be dissolved in 3 mL of solvent)

The effect of the length of the alkyl substituent on the solubilities of the compounds in acetone, isopropanol, ethyl acetate and toluene can be observed. The IL with the shortest chain, **18**, exhibits good solubility in these solvents. In turn, ILs **19** and **20** with the octyl and decyl alkyl chains, respectively, are characterized by limited solubility in acetone and isopropanol, while they are completely insoluble in ethyl acetate and toluene. With the increase in the alkyl chain length to dodecyl for **21** and tetradecyl for **22**, an improvement in the solubility in the abovementioned solvents is observed. After a comparison of the effect of the ring substitution of the phenoxy group in the cation, it can be observed that ILs **15**, **16** and **18** exhibit good solubility in all of the tested solvents except hexane. On the other hand, **17**, which possesses chlorine in the phenoxy group, is characterized by limited solubility in acetone and isopropanol and low solubility in ethyl acetate and toluene.

The thermal stability was measured as both the onset temperature needed for 5% sample decomposition ($T_{5\%}$) and the 50% decomposition temperature ($T_{50\%}$). Comparison of the thermal stability between all prepared compounds was performed by assessing the onset of thermal decomposition for the first 5% weight loss ($T_{5\%}$), which provides a more accurate assessment of the thermal stability than the 50% onset of thermal decomposition. The thermal decomposition of ILs begins in the range of 170–200 °C, as shown in Table 5. IL **23** exhibits the highest thermal stability. It is the only compound among the tested ionic liquids that exhibits a $T_{5\%}$ above 200 °C as well as the only one that includes a propyl group in the cation and not an ethyl group. The thermal stability of the tested ILs increases with the increase in the length of the alkyl substituent in the cation, from 176 for **18** to 192 °C for **21** and **22**. The presence of substituents (chlorine and methyl group) in the phenoxy group ring negatively affects the temperature stability. For **16–18** $T_{5\%}$

is within the range of 176–179 °C. In the case of **15**, which does not possess any ring substituents, $T_{5\%} = 191$ °C. The melting point and the crystallization temperature could only be determined for **24** and are equal to 72.5 °C and 45.9 °C, respectively. For all of the synthesized ILs, it was possible to determine the glass transition temperature, which is in the range from −29.6 for **22** to −11.2 °C for **16**. A decrease in the glass transition temperature with increasing length of the alkyl substituent in the cation can be observed.

The herbicidal activity of the synthesized ILs was tested against cornflower (*Centaurea cyanus* L.). The herbicidal activity was determined based on the results of biological tests carried out in a greenhouse. The commercially available product Chwastox Extra 300 SL, which contains MCPA sodium and potassium salt as the active substance, was used as a control. The products were used at a dose of 400 g of MCPA per hectare. The obtained results indicate that all of the tested ILs exhibit high herbicidal activity. Ion acetate of MCPA was the anion in all ILs, and therefore, their use caused symptoms typical for phenoxyacetic acid herbicides. In the initial stage, epinasty and the inhibition of growth cone activity occurred, followed by chlorosis, eventually leading to the necrosis of plant tissues (Coob and Reade 2010). Photographs of plants 14 days after the application of compounds are included in the ESI, (ESI Fig. 79). The plant fresh biomass reduction results are shown in Fig. 1. All ILs showed activity greater than 95%, which is at the commercial product level.

In case of ring substituent configuration in obtained ILs, the alkyl substituent and the presence of the chlorine atom or methyl group in the ring in the cation practically do not affect the herbicidal activity. The activity of the anion, ion acetate of MCPA, was preserved in the tested ILs. New HILs were obtained, i.e. MCPA in the form of ILs as derivatives of domiphen with recognized antibacterial and antiseptic properties.

The first stage of research on ionic liquids with domiphen derivatives as a cation has been completed. The prepared ionic liquids are effective at the same level as commercially available MCPA in the form of sodium or potassium salt. The chemical characteristics of the obtained ionic liquids have been presented. However, for full understanding of the biodegradation pathway and microbial degradation of chemical compounds in the environment, the new investigation is necessary.

Table 5 DSC and TG analysis of the synthesized ILs (**15–24**)

IL	T_g (°C)	T_c (°C)	T_m (°C)	$T_{5\%}$ (°C)	$T_{50\%}$ (°C)
15	−17.8	–	–	190	224
16	−11.2	–	–	179	211
17	−12.5	–	–	176	204
18	−11.8	–	–	175	205
19	−19.7	–	–	190	223
20	−25.8	–	–	190	225
21	−23.4	–	–	192	232
22	−29.6	–	–	192	240
23	−14.4	–	–	200	235
24	−25.6	45.9	72.5	186	224

T_m—melting point; T_c—temperature of crystallization; T_g—glass transition temperature; $T_{5\%}$—decomposition of 5% of sample; $T_{50\%}$—decomposition of 50% sample
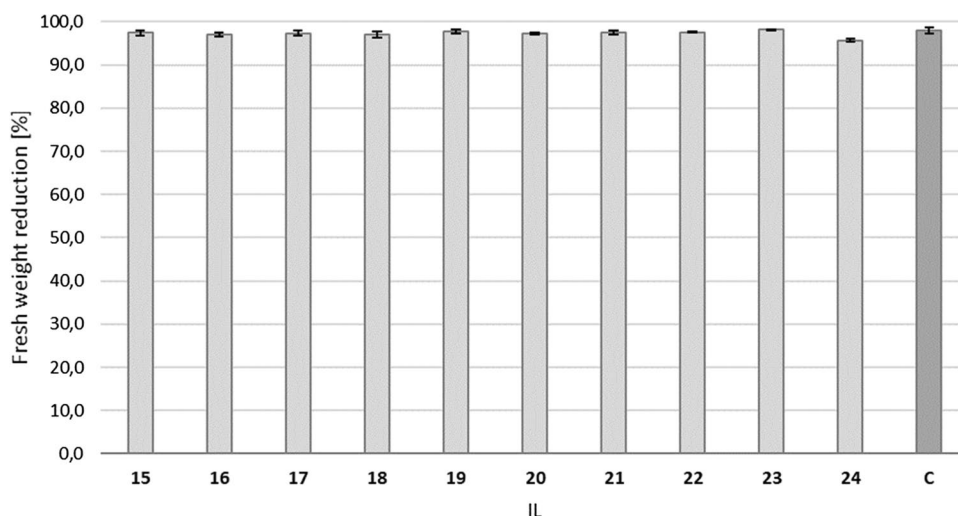
Conclusions

Ten novel ILs were obtained. They consisted of a (4-chloro-2-methylphenoxy)acetate anion and an *N*-alkyl-*N*,*N*-dimethylphenoxyammonium cation with an alkyl substituent length from

Fig. 1 Herbicidal activity of the synthesized ILs (**15**–**24**), *C*–control

hexyl to tetradecyl and the substitution of the phenol ring at the *para* and *meta* positions with a chlorine atom and a methyl group. They are also new derivatives of domiphen, a quaternary ammonium bromide with well-known antibacterial and antiseptic properties. The four-step synthesis strategy involved the preparation of phenoxyamines in the Williamson reaction with yields in the range of 61–78%, which were alkylated with 1-bromoalkanes in the Menshutkin reaction with yields of 80–93%. After the ion exchange, the synthesis of ILs was performed by neutralizing the synthesized hydroxides with (4-chloro-2-methylphenoxy)acetic acid (MCPA) with yields of 93–99%. The synthesized ILs exhibit thermal stability up to 175 °C and are characterized by high herbicidal activity against cornflower (*Centaurea cyanus* L.). The fresh weight reduction exceeded 95% in all cases. The obtained results allowed the tested compounds to be classified as HILs, in which the activity of the MCPA anion was preserved. They are also new derivatives of domiphen, a quaternary ammonium bromide with well-known antibacterial and antiseptic properties. However, it cannot be clearly stated whether the effectiveness of the synthesized ionic liquids (**15**–**24**) is related solely to the presence of the MCPA ion or also to the presence of the phenoxyethylammonium cation. Therefore, in the second stage of this research, on this group of compounds, additionally the herbicidal and bactericidal activity of the raw materials used for synthesis, quaternary bromides (**6**–**14**) and hydroxides used for their synthesis should be checked. The obtained results will make it possible to unequivocally assess which part of the ionic liquids (cation or anion) is responsible for biological activity and may have an impact on the use of the tested products in agriculture.

Declarations

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