SYNTHESIS OF NEW SALTS AND ION-PAIR COMPOUNDS OF SALICYLIC ACID, STRUCTURAL ANALYSIS AND THEIR EFFECTS ON TOMATO SEED GERMINATION AND SEEDLING GROWTH

V.M. Abbasov, R.A. Asadova, R.Z. Bagyrzadeh, A.H. Farzaliyev, P.A. Movsumova, A.R. Azizbayli, H.R. Azizbayli, S.S. Suleymanova, N.M. Mammadova

Institute of Petrochemical Processes named after Academician Yusif Mammadaliyev of the Ministry of Science and Education of the Republic of Azerbaijan, AZ 1025, Baku, 30 Khojaly ave.
Phone: +994 50 529 10 93
r.asadova88@mail.ru

Received 09.07.2026
Accepted 22.10.2026

Abstract: *This article presents the synthesis of new plant growth stimulants intended to promote the growth of tomato plants. The synthesized compounds were simultaneously characterized using spectroscopic and physicochemical methods. The sodium and potassium salts of salicylic acid, as well as their corresponding triethanolamine and isobutylamine ion-pair compounds, were synthesized using sodium hydroxide, potassium hydroxide, triethanolamine, and isobutylamine, respectively. Aqueous solutions of salicylic acid compounds with sodium, potassium, triethanolamine, and isobutylamine were prepared at various concentrations, and their effects on tomato seeds were investigated. The effects of solutions containing triethanolamine and isobutylamine ion-pair compounds of salicylic acid on plant development as growth stimulants were examined for the first time in agricultural applications.*

The synthesized compounds were characterized using FT-IR and $^{1}H/^{13}C$ NMR spectroscopy, while their thermal properties and stability were assessed by thermogravimetric analysis using an STA 449 F3 Jupiter thermal analyzer under a nitrogen atmosphere over the temperature range of 23–650 °C at a heating rate of 20 °C min^{-1}. The effects of salicylic acid–triethanolamine and salicylic acid–isobutylamine ion-pair compounds on plant development as growth stimulants were investigated for the first time in the field of agriculture.

Biological assays were conducted using seeds of the tomato variety "Zarrabi," which was zoned in 2001 and obtained from the Scientific Research Institute of Vegetable Growing of the Republic of Azerbaijan. Seed germination percentage, along with the root and shoot lengths of the resulting seedlings, was determined.

The results demonstrated that the ionic compounds of salicylic acid with triethanolamine and isobutylamine exhibit higher water solubility than the other compounds investigated. Furthermore, their 0.0001% aqueous solutions significantly promote root and shoot growth in tomato seedlings.
Keywords: *salicylic acid, triethanolamine, isobutylamine, plant stimulant, tomato seeds*

Introduction

Growing concerns about environmental contamination and food safety have arisen due to the widespread misuse and overuse of chemical pesticides in modern agriculture. This has stimulated the search for sustainable alternatives capable of promoting plant growth without posing risks to human health or the environment. Among these alternatives, plant growth-promoting compounds that improve plant development and enhance natural defense mechanisms have attracted considerable scientific interest. Strengthening plant immunity not only contributes to healthier growth but also helps protect crops against infectious diseases, thereby decreasing the need for conventional chemical plant protection products. Consequently, environmentally friendly agricultural practices and biological disease management strategies have become increasingly important. In this context, biogenic chemical compounds have emerged as promising agents for enhancing the systemic disease resistance of plants.

Recent studies have identified salicylic acid (SA) as a potential inducer of systemic resistance in plants. Several SA derivatives have been shown to enhance the activation of plant defense responses, thereby improving resistance to a variety of plant pathogens and diseases [1, 2]. Previous

studies by Raskin have shown that SA occurs naturally in trace amounts in the leaves, roots, flowers, and fruits of many plant species [3].

In aqueous solution, sodium salicylate dissociates to form salicylic acid. SA is a key phenolic plant signaling molecule and an important regulator of plant physiological processes [4]. Owing to their strong biological activity, phenolic compounds are widely used in agriculture. Several members of this group serve as active components in plant protection products, including pesticides and insecticides, while others are considered promising agents for plant growth regulation and for enhancing resistance to phytopathogenic organisms [5, 6].

SA plays a central role in systemic acquired resistance as well as in the hypersensitive response of plants to temperature stress, contributing to both acquired and basal thermotolerance. In tomato plants, SA has been reported to increase the accumulation of heat shock proteins, particularly Hsp70, thereby improving tolerance to high temperatures. In addition, SA treatment enhances the activity of heat shock factors and upregulates Hsp70 gene expression, resulting in improved adaptation to heat stress conditions [7-11]. Recent studies also suggest that SA can enhance both cold and heat tolerance in several vegetable crops (including cucumber) [11, 12]. The influence of dinitrosalicylic acid (DNSA) on the antioxidant defense system of cotton seedlings has been demonstrated to be concentration-dependent [12]. At low concentrations, DNSA was found to reduce the activity of catalase and polyphenol oxidase enzymes, decrease nitric oxide (NO) levels, and inhibit phosphate ion uptake, whereas at higher concentrations it increased peroxidase activity and restored NO production. In addition, DNSA contributed to the regulation of plant stress responses by increasing the level of lipid peroxidation radicals.

In recent years, a number of studies have been conducted at the Institute of Petrochemical Processes aimed at developing new plant growth-promoting compounds. Within these studies, the effects of aqueous solutions of salts of natural naphthenic acids, chitosan, salicylic acid, and succinic acid on seed germination, plant development, and productivity have been systematically investigated under both laboratory and field conditions at the “Biologically Active Natural Compounds” laboratory of the institute. The obtained results have demonstrated that these compounds are promising for stimulating plant growth and enhancing resistance to various stress factors [13-16].

The role of salicylic acid and its derivatives in regulating plant growth and stress tolerance processes has been demonstrated in various studies. Furthermore, the physicochemical properties of various salt forms and amine-containing compounds of salicylic acid can influence the nature of their biological activity. Studies on the physicochemical properties of salts formed by organic acids with triethanolamine also show that the properties of such ion-pair systems depend on the structure of both the acid and the amine component. However, the comparative evaluation of the structural and thermal properties of salicylic acid compounds obtained with triethanolamine and isobutylamine, alongside their effect on tomato seed germination and early seedling development, has not been sufficiently investigated. Therefore, the comparative study of these compounds alongside sodium and potassium salicylates under identical experimental conditions is of significant interest for evaluating their potential plant-growth-stimulating activity.

Additionally, a copolymer based on allyl salicylate and N,N′-(p-phenylene)bismaleimide was synthesized, and its structure was investigated using spectroscopic methods. The FT-IR, ^{1}H NMR, and ^{13}C NMR spectra of the copolymer, along with its physicochemical properties, were examined. Furthermore, the antimicrobial activity of the synthesized copolymer was evaluated [17]. In a separate study [18], Cu(II), Ni(II), and Co(II) complexes based on salicylic acid hydrazide derivatives were synthesized, and their structures were investigated using elemental analysis, IR and electronic spectroscopy, magnetochemical measurements, and thermal analysis. The antioxidant and urease inhibitory activities of these complexes were also investigated, revealing significant activity. Fe(III), Mn(II), and Cu(II) complexes based on salicylic acid hydrazide were synthesized, and their structures were characterized using elemental analysis, magnetic susceptibility measurements, and thermal analysis. The investigated complexes were found to exhibit distorted octahedral geometries [19].

Salicylic acid (SA) plays an important role in regulating photosynthetic parameters and water balance by influencing various metabolic and physiological processes in plants. Hayat et al. reported that seedlings grown from wheat grains treated with low concentrations of salicylic acid (10^{-5} M) exhibited increased photosynthetic pigment content; however, this beneficial effect was not observed at higher concentrations. These findings indicate that the influence of salicylic acid on plant physiological processes is concentration-dependent [20, 21].

Considering that plants primarily absorb nutrients and biologically active substances in water-soluble forms, the synthesis of new, highly water-soluble derivatives of salicylic acid was considered a promising approach to improving its solubility and facilitating its uptake by plants. In this context, the preparation of ion-pair compounds of salicylic acid with triethanolamine (TEA) and isobutylamine (IBA) is of particular interest. A comparative investigation of these compounds and sodium and potassium salicylates is important for assessing their potential plant growth-stimulating activity.

The aim of the present study is to synthesize sodium and potassium salts of salicylic acid, along with its ion-pair compounds with TEA and IBA, to comparatively investigate their structural, thermal, and physicochemical properties, and to evaluate their effects on tomato seed germination and early seedling development. The scientific novelty of this work lies in the characterization of the synthesized salicylic acid compounds with TEA and IBA using FT-IR and $^{1}H/^{13}C$ NMR spectroscopy and thermal analysis, as well as in the comparative evaluation of the effects of their aqueous solutions at various concentrations, including 0.0001%, on tomato seed germination and seedling root and shoot development relative to sodium and potassium salicylates.

Experimental part

Salicylic acid (SA) salts and ion-pair compounds were synthesized, and their aqueous solutions at concentrations of 1%, 0.01%, 0.001%, and 0.0001% were prepared to investigate their effects on tomato seed germination.

The synthesis of SA salts and ion-pair compounds was performed at the “Biologically Active Natural Compounds” Laboratory of the Institute of Petrochemical Processes using a three-necked reaction flask equipped with a mechanical stirrer, a heating system, and a thermometer.

The reaction mixture was maintained at 50–60 °C under continuous stirring for 30–40 minutes until salt formation was complete. For the synthesis of ion-pair compounds of salicylic acid with triethanolamine and isobutylamine, a calculated amount of salicylic acid (SA) was introduced into the reaction flask, followed by the addition of triethanolamine or isobutylamine, respectively. The reactions were conducted at 40–50 °C for 50–60 minutes. As a result of the acid–base interaction, proton transfer from the carboxyl group of salicylic acid to the nitrogen atom of the corresponding amine leads to the formation of the respective ammonium salicylate salts.

Structural schemes of the ion-pair compounds formed between salicylic acid and triethanolamine or isobutylamine:

Salicylic acid-triethanolamine:

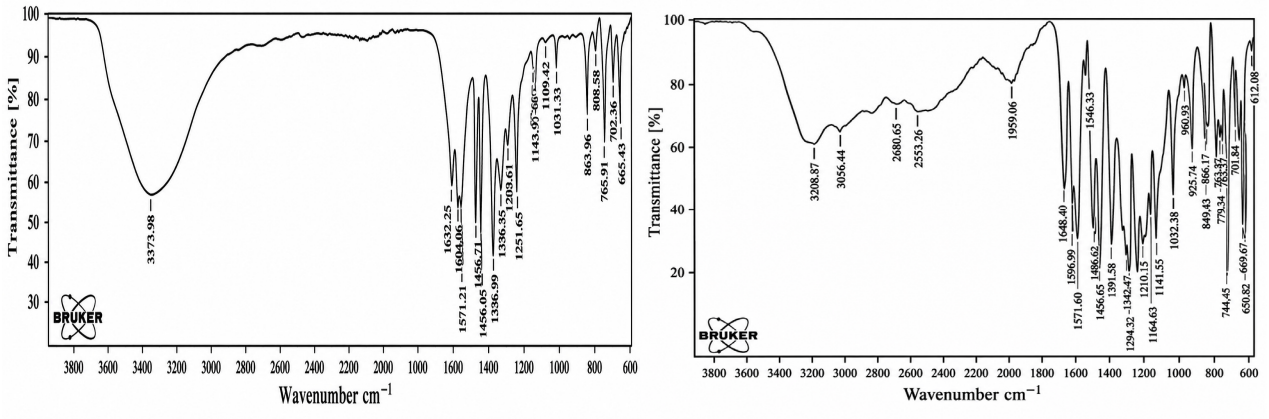
$$C_6H_4(OH)COOH+N(CH_2CH_2OH)_3 \rightarrow [C_6H_4(OH)COO]^-[H_3N(CH_2CH_2OH)_3]^+$$

Salicylic acid-isobutylamine:

$$C_6H_4(OH)COOH+H_2NCH_2CH(CH_3)_2 \rightarrow [C_6H_4(OH)COO]^-[H_3NCH_2CH(CH_3)_2]^+$$

Results and discussion

The composition of the sodium and potassium salts of SA, as well as their TEA and IBA ion-pair compounds, was confirmed by FT-IR and $^{1}H/^{13}C$ NMR spectroscopy. The ^{1}H NMR and ^{13}C NMR data are presented separately below (Figs. 1-4).

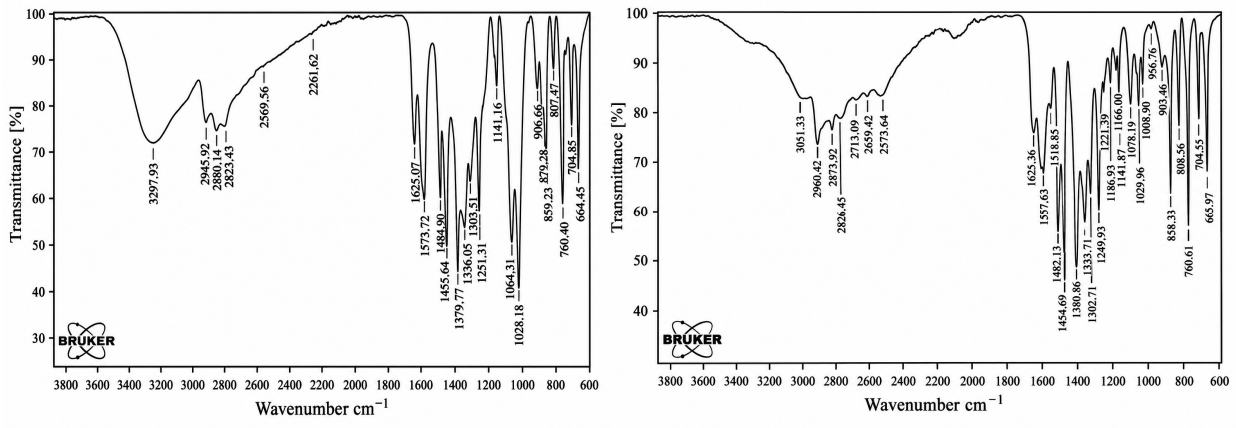


a) b)

Fig. 1. FT-IR spectra of sodium (a) and potassium (b) salts of SA

In the FT-IR spectrum of the sodium salt of SA, the absorption bands characteristic of salicylic acid at 1654 and 1609 cm^{-1} disappeared, and new absorption bands characteristic of the carboxylate ion (COO^-) appeared at 1590 and 1623 cm^{-1} (Fig. 1a). The band at 1623 cm^{-1} was attributed to the asymmetric [$\nu_{as}(COO^-)$] valence vibration of the COO^- group, and the band at 1590 cm^{-1} was attributed to the symmetric [$\nu_s(COO^-)$] valence vibration. The frequency difference between these bands was 33 cm^{-1} according to the formula $\Delta\nu = \nu_{as}-\nu_s$.

In the FT-IR spectrum of the potassium salt of SA, the absorption bands at 1654 and 1609 cm^{-1} characteristic of salicylic acid disappeared, and new absorption bands at 1571, 1596 and 1648 cm^{-1} were observed (Fig. 1b). The band at 1596 cm^{-1} was attributed to the asymmetric [$\nu_{as}(COO^-)$] valence vibration of the COO^- group, and the band at 1571 cm^{-1} was attributed to the symmetric [$\nu_s(COO^-)$] valence vibration. For this sample, $\Delta\nu$=1596-1571=25 cm^{-1}.



a) b)

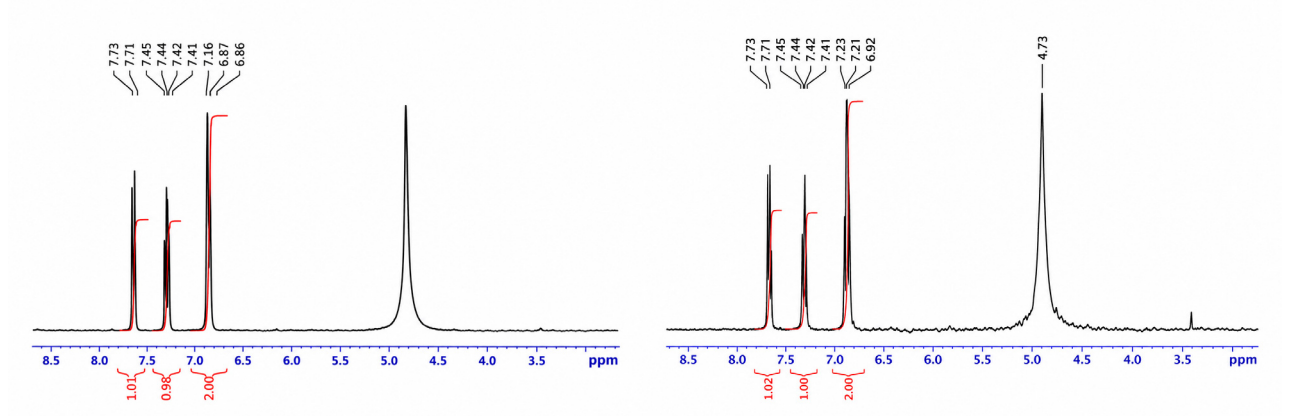
Fig. 2. FT-IR spectra of the TEA (a) and IBA (b) ion-pair compounds of SA

In the spectrum of the ion combination of SA with TEA, an absorption band characteristic of the carboxyl ion (-COO^-) at 1625 cm^{-1}, 1573 cm^{-1}, and absorption bands characteristic of NH^+ amine at 2261 cm^{-1}, 2569 cm^{-1} appear (Fig. 2a). The absorption bands observed at 1625 and 1573 cm^{-1} in the FT-IR spectrum of the TEA ion compound of SA were attributed to the asymmetric [$\nu_{as}(COO^-)$] and symmetric [$\nu_s(COO^-)$] valence oscillations of the COO^- group, respectively. The frequency difference between these bands was $\Delta\nu$=1625-1573=52 cm^{-1}. In addition, absorption bands observed at 2261 and 2569 cm^{-1} were attributed to the presence of a protonated amine component.

In the spectrum of the ion combination of SA with IBA, an absorption band characteristic of carboxyl ion (-COO^-) at 380 cm^{-1}, 1454 cm^{-1}, 1557 cm^{-1}, and an absorption band characteristic of NH^+ amine at 2573 cm^{-1}, 2659 cm^{-1}, 2713 cm^{-1} are observed (Fig. 2b). The absorption bands

observed at 1557 and 1454 cm^{-1} in the FT-IR spectrum of the IBA compound of SA were attributed to the asymmetric [$\nu_{as}(COO^-)$] and symmetric [$\nu_s(COO^-)$] valence oscillations of the COO^- group, respectively. For this sample, $\Delta\nu$=557-1454=103 cm^{-1}. The absorption bands observed at 2573, 2659 and 2713 cm^{-1} were associated with the presence of the protonated amine component.

Thus, observation of absorption bands related to asymmetric and symmetric valence oscillations of the COO^- group in FT IR spectra and determination of $\Delta\nu$ values between them can be considered as spectral indicators confirming that the carboxyl group of salicylic acid is deprotonated and in salicylate form.



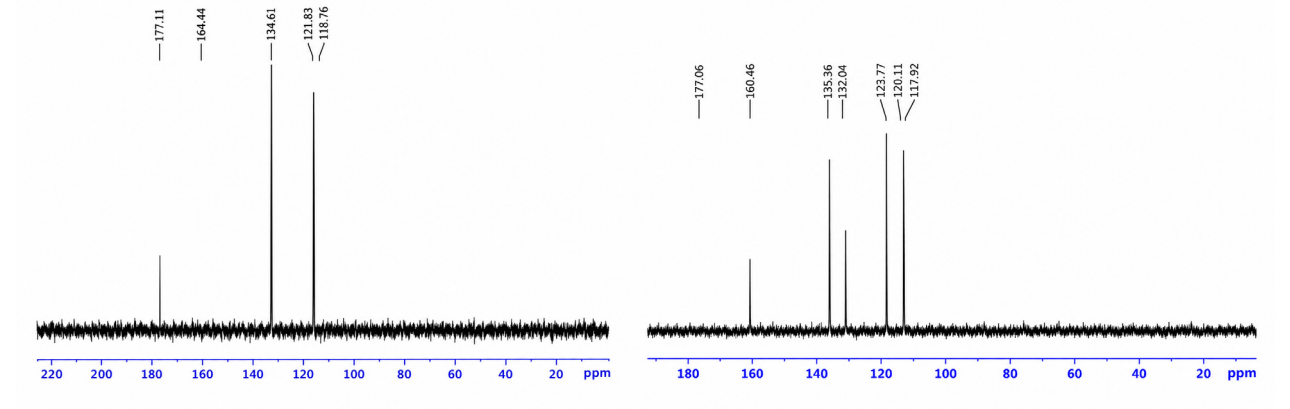
a) b)

Fig. 3. ^{1}H-NMR spectra of the sodium (a) and potassium (b) salts of SA

The ^{1}H and ^{13}C NMR spectra of the sodium and potassium salts of SA as well as the ion-pair compounds obtained with TEA and IBA, were investigated. The ^{1}H and ^{13}C NMR spectra were recorded at room temperature (20 °C) using a Fourier 300.18 MHz spectrometer manufactured by Bruker (Germany). Tetramethylsilane (TMS) was used as the internal standard, and heavy water (D_2O) served as the solvent.

In the ^{1}H NMR spectrum of the sodium salt of SA, resonance signals corresponding to the hydrogen atoms of the aromatic ring were observed at δ 6.75-6.86 ppm (m, 2H), δ 7.27-7.32 ppm (m, 1H), and δ 7.67 ppm (dd, 1H, J=7.8 and 1.5 Hz). The proton of the OH group was not observed separately in the ^{1}H NMR spectrum due to exchange with D_2O (Fig. 3a).

In the ^{1}H NMR spectrum of the potassium salt of SA, resonance signals observed at δ 6.82 (2H), δ 7.32 (1H), and δ 7.68 (1H) ppm were assigned to the hydrogen atoms of the aromatic ring (Fig. 3b).

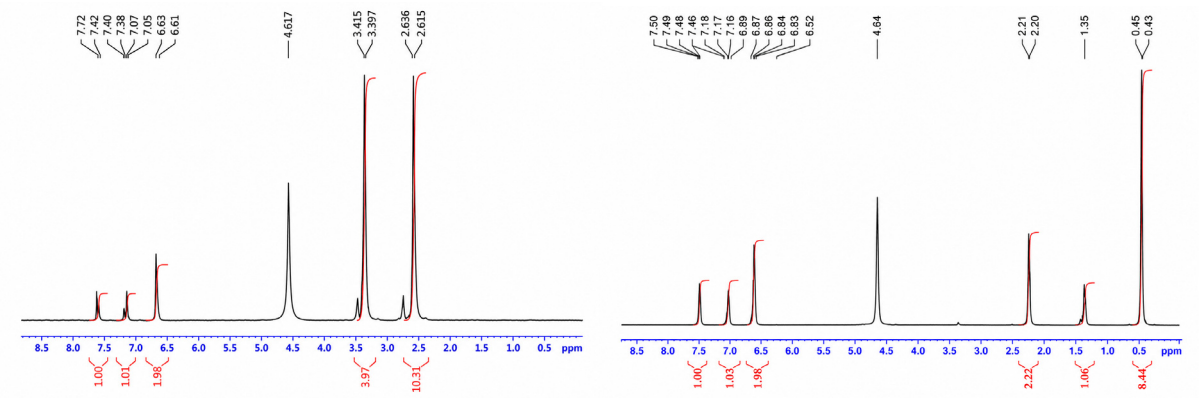


a) b)

Fig. 4. ^{13}C-NMR spectra of the sodium (a) and potassium (b) salts of SA

Resonance signals corresponding to the carbon atoms of the aromatic core were observed in the ^{13}C NMR spectra of the sodium and potassium salts of SA. For the sodium salt, signals corresponding to aromatic carbon atoms were recorded at δ 11.21, 117.90, 119.27, 130.39, and δ

133.89 ppm; the signal for the carbon atom of the C-OH group was observed at δ 159.53 ppm; and the signal for the carbon atom of the -COO^- group was recorded at δ 175.55 ppm (Fig. 4a). The corresponding ^{13}C NMR signals for the potassium salt (Fig. 4b) are presented.

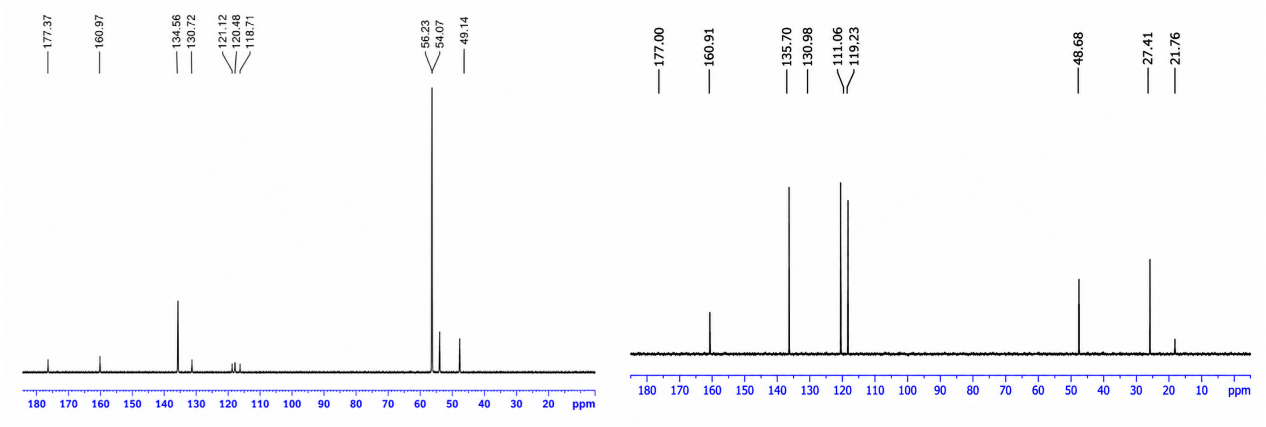


a) b)

Fig. 5. ^{1}H-NMR spectra of the TEA (a) and IBA (b) ion-pair compounds of SA

In the ^{1}H NMR spectrum of the ion-pair compound formed by SA and TEA, the resonance signals observed at δ 2.55 and 3.35 ppm were assigned to the hydrogen atoms of the CH_2 groups, while the signals recorded at δ 6.54, 7.01, and δ 7.47 ppm were attributed to the hydrogen atoms of the aromatic ring (Fig. 5a).

In the ^{1}H NMR spectrum of the ion-pair compound formed by SA and IBA, the resonance signal corresponding to the hydrogen atoms of the methyl groups was observed at δ 0.49 ppm (d, 6H, J=6.6 Hz), the signal for the CH group proton at δ 1.46 ppm (m, 1H), and the signal for the CH_2 group protons at δ 2.35 ppm (d, 2H, J=7.2 Hz). Resonance signals corresponding to the aromatic ring hydrogen atoms were recorded in the ranges of δ 6.48–6.53 ppm (m, 2H) and δ 6.90-6.99 ppm (m, 1H), as well as at δ 7.47 ppm (dd, 1H, J=8.1 and 1.8 Hz). Since the hydroxyl group proton undergoes exchange with D_2O, no distinct resonance signal for it was observed in the ^{1}H NMR spectrum (Fig. 5b).



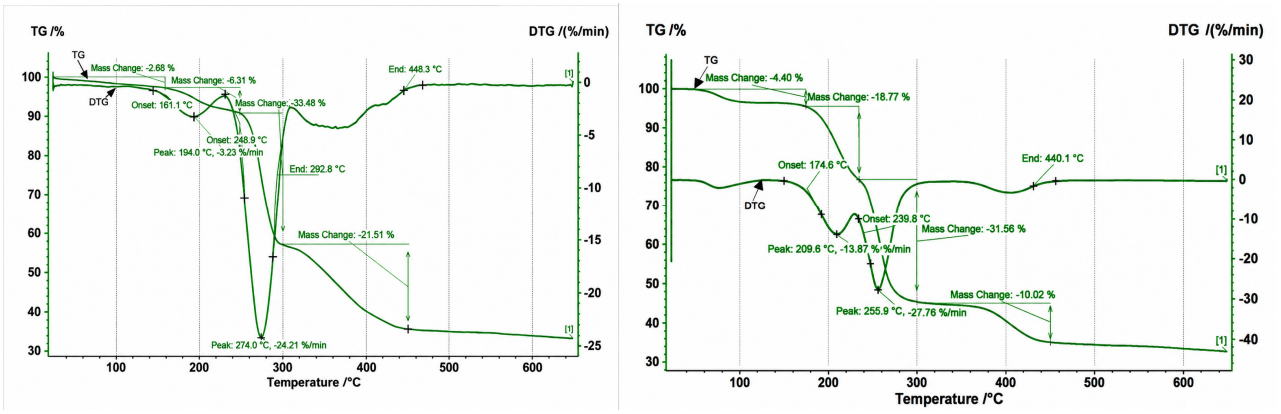
a) b)

Fig. 6. ^{13}C-NMR spectra of the TEA (a) and IBA (b) ion-pair compounds of SA

In the ^{13}C NMR spectrum of the ion-pair compound formed by SA and IBA, the resonance signal corresponding to the methyl group carbons -CH_3 was recorded at δ 18.61 ppm, the signal for the -CH- group carbon at δ 26.07 ppm, and the signal for the -CH_2-N- group carbon at δ 46.05 ppm. Resonance signals corresponding to the aromatic ring carbons (-CH=) were observed at δ 116.05, 117.83, 119.02, 130.25, and 133.64 ppm. The signal for the phenolic text C-OH group carbon was recorded at δ 159.59 ppm, while the signal for the carboxylate group carbon (-COO^-) appeared at δ 175.11 ppm (Fig. 6a and 6b).

Thus, the $^{1}H/^{13}C$ NMR spectra of the SA salts show that protons belonging to the aromatic ring were observed, whereas the hydrogen atom associated with the carboxyl group was not detected, indicating that this proton had been substituted.

In addition, the thermal properties of the samples were investigated using thermogravimetric (TG/TGA) and differential thermogravimetric (DTG) analysis methods (Fig.s 7a, b and 8a, b). The analyses were performed using a simultaneous thermal analyzer (NETZSCH STA 449F3 Jupiter, Germany) in an inert atmosphere (N_2) over a temperature range of 23-650 °C. The heating rate was 20 °C/min, the N_2 gas flow rate was 20 mL/min, and the sample mass was 5-7 mg. Thermal properties were evaluated based on the combined analysis of TG and DTG curves.



a) b)

Fig. 7. TG/DTG curves of the sodium (a) and potassium (b) salts of SA

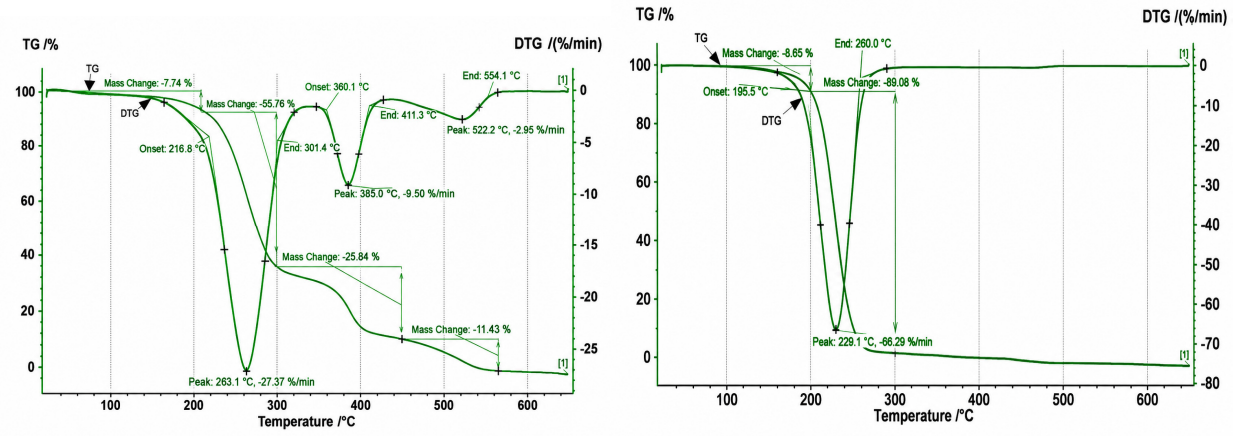
Based on the provided thermogravimetric TG/DTG curve, it can be stated that the initial mass loss occurs as the temperature rises, resulting from physical processes such as softening and the transition to a liquid state in the samples (Fig.s 7a and 7b).

The analysis of the TG/DTG curves of sodium salicylate indicates that mass loss occurs in four main stages (Fig. 7a). The first stage takes place in the temperature range of 25-161.1°C, corresponding to a mass loss of approximately 2.68%. The second stage occurs within 161.1-248.9°C, resulting in a 6.31% mass loss; the peak observed at 194.0°C on the DTG curve reflects an increase in the intensity of this thermal transformation. In the third stage, 248.9-300°C, a sharp mass loss of 33.48% is observed, with a DTG maximum recorded at 274°C. This stage can be attributed to the intensive thermal decomposition of the organic salicylate moiety. In the fourth stage 300-450 0C, an additional mass loss of 21.51% occurs, which corresponds to the further degradation of thermal decomposition products formed in the preceding step and the formation of a more stable residual compound.

Four main stages of mass loss are also observed in the TG/DTG curves of potassium salicylate (Fig. 7 b). The first stage occurs in the temperature range of 25-174.6°C and is characterized by a minor mass loss of 4.40%. The second stage takes place within 175-235°C, exhibiting a mass loss of 18.77%. In the third stage, a significant mass loss of 31.55% is recorded over the temperature interval of 240-300°C. The fourth stage spans the range of 300-450°C with a mass loss of 10.02%, corresponding to the further degradation of the thermal decomposition products formed in the preceding steps and the ultimate formation of a stable residue. On the DTG curve, distinct peaks are observed at 209.6°C and 255.9°C, the latter representing the maximum rate of mass loss.

The analysis of the TG/DTG curves of the SA-TEA ion-pair compound indicates four main stages of mass loss (Fig. 8a). The first stage occurs in the temperature range of 25-217°C with a mass loss of 7.74%. The second stage takes place within 217-300°C and is characterized by a significant mass loss of 55.76%. In the third stage, 300-450°C, a mass loss of 25.84% is observed, with the maximum decomposition rate recorded at 385°C. The fourth stage spans 450-565°C with

an additional mass loss of 11.43%. Overall, maximum degradation rates (DTG peaks) for these steps are observed at 263.1°C, 385.0°C, and 522.2°C, respectively.



a) b)

Fig. 8. TG/DTG curves of the TEA (a) and IBA (b) ion-pair compound of SA

In contrast to the TEA derivative, the thermal decomposition of the SA-IBA ion-pair compound proceeds in two main stages (Fig. 8 b). The first stage takes place in the range of 25-195 ºC with a mass loss of 10.43%. The second stage occurs between 200-300 ºC, exhibiting a major mass loss of 86.21%, which corresponds to the intensive thermal degradation of the organic components. The minor mass remaining above 300 ºC can be attributed to the formation of a thermally stable residue. The characteristic maximum peak on the DTG curve is recorded at 245.9 ºC. The thermal properties of the four investigated samples were comprehensively determined using TG/DTG analysis. Mass loss occurs in four distinct stages for the sodium and potassium salts of SA, whereas the TEA and IBA ion-pair compounds undergo decomposition in four and two main stages, respectively. The mass losses observed at higher temperatures are primarily attributed to the thermal degradation of the organic moieties. The distinct thermal degradation profiles of the SA-TEA and SA-IBA compounds demonstrate that their thermal behavior is strongly influenced by their structural characteristics and counterion nature.

Table. Physicochemical properties of 40% aqueous solutions of SA compounds

Parameters	Sodium salt of SA	Potassium salt of SA	TEA complex of SA	IBA complex of SA	Test methods according to NTS
Density (20 ºC), g/cm^3	1.0047	1.0173	0.9860	1.0704	ASTM D5002-18e1
Freezing point, ºC	-9	-5	-11	-7	ASTM D97-17b
pH	7.0-8.0	7.0-8.0	7.5-8.0	7.5-8.0	-

An investigation into the physicochemical properties of 40% aqueous solutions of the synthesized SA compounds revealed that the highest density was recorded for the ionic compound of SA with IBA (1.0704 g/cm³), while the lowest density was observed for the ionic compound of SA with TEA (0.9860 g/cm³). The lowest freezing point was determined for the ionic compound of SA with TEA (-11 ºC), and the highest for the potassium salt of SA (-5 ºC). The pH values ranged from 7.0 to 8.0 for aqueous solutions of the sodium and potassium salts of SA, and from 7.5 to 8.0 for solutions of the ionic compounds with TEA and IBA. Thus, all the solutions studied exhibited a neutral to slightly alkaline character. The synthesized sodium and potassium salts and the IBA ionic compound appear as white crystalline powders, whereas the TEA ionic compound is a yellowish substance.

Biological assays were conducted using tomato seeds of the "Zarrabi" variety, approved for cultivation in 2001, obtained from the Vegetable Growing Research Institute of the Republic of Azerbaijan. The experiments were carried out at room temperature (22°C) and a relative humidity of 65-75%. Observations continued for 30 days. The emergence of the radicle from the seed was adopted as the criterion for germination. Measurement of the root and shoot lengths of the seedlings began on the 12th-14th day of the experiment. In the initial stage of the biological assays, aqueous solutions of the salicylic compounds under study were prepared at concentrations of 0.1%, 0.01%, 0.001% and 0.0001%, and their effects on tomato seed germination and seedling development were comparatively evaluated.

Based on the results of the preliminary tests, a stimulatory effect was observed in tomato seeds treated with the 0.0001% aqueous solution, and this concentration was selected for subsequent main biological experiments. Key biological tests demonstrated that 0.0001% aqueous solutions of ionic compounds formed by SA with TEA and IBA positively influenced the root and shoot development of seedlings grown from tomato seeds. The impact of these aqueous solutions on plant growth and development parameters was investigated for the first time in the agricultural sector.

The experiments were conducted at the "Functional Analysis" laboratory of the Scientific Research Institute of Vegetable Growing. Studies involving tomato seeds were carried out using Petri dishes, with 20 seeds placed in each dish across three replicates. Ten milliliters of the prepared solutions were added to each Petri dish, while an equal volume of distilled water was applied to the seeds in the control group. After soaking in the solutions for 24 hours, the seeds were removed and transferred to new Petri dishes. In the subsequent days, the seeds were supplied only with irrigation water.

The obtained results demonstrated that the germination rate of tomato seeds treated with 0.0001% solutions of the salicylic SA-indole-3-butyric acid (IBA) ion-pair compound and the sodium salt of SA reached 100%, which was comparable to that of the control treatment. In contrast, treatment with the SA-triethylamine (TEA) ion-pair compound and the potassium salt of SA resulted in a germination rate of 97%.

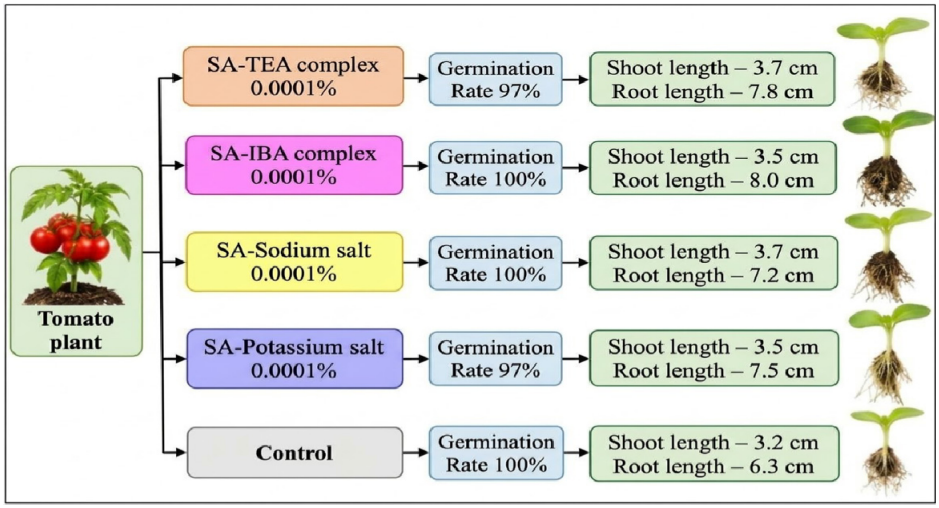
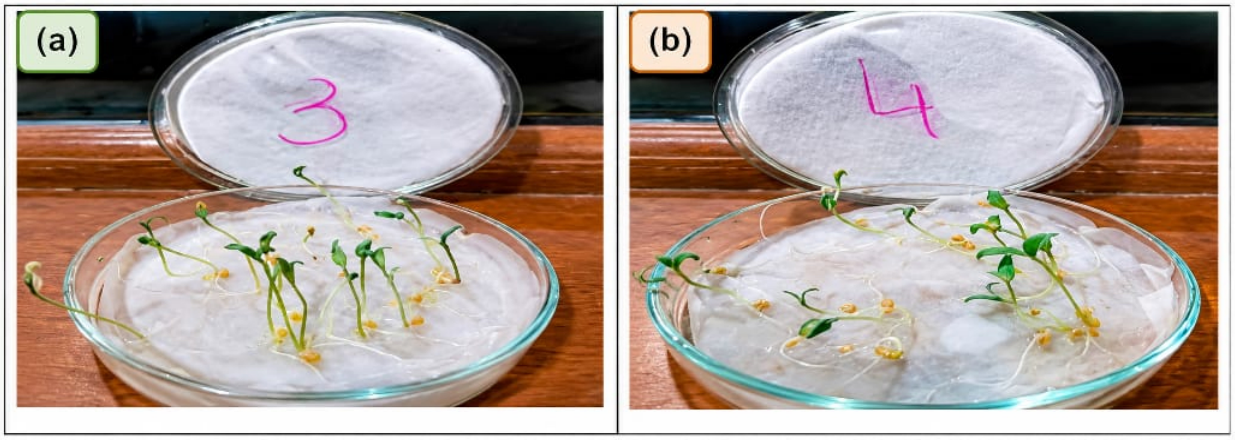


Diagram. Effect of salt and ionic compounds of SA on the development of tomato seedlings

Furthermore, all of the investigated SA-based compounds exerted a positive effect on the growth of both the aerial parts and roots of the seedlings. The most pronounced increase in shoot length (15.6% relative to the control) was observed following treatment with the SA-TEA ion-pair compound and the sodium salt of SA. In seedlings treated with the SA-IBA ion-pair compound and the potassium salt of SA, shoot length increased by 9.4% compared with the control treatment. All the solutions studied were found to have a positive effect on root length. The greatest increase in root length was observed with the application of the ion-pair compounds of SA with IBA and TEA, amounting to 27.0% and 23.8%, respectively, compared to the control variant. In solutions of the

sodium and potassium salts of SA, the increase in root length was 14.3% and 19.1%, respectively (Scheme).

An increase in biomass, as well as an improvement in the development metrics of vegetative organs such as stems and roots, was observed in plants treated with SA compared to the control group. The results suggest that salt and ionic compounds of SA can exert a stimulatory effect on the germination and early development of tomato plants.



a b

Fig. 9. Comparison of tomato seedlings treated with a 0.0001% aqueous solution of the SA-IBA ionic compound (a) with control seedlings

As shown in Figure 9, tomato seedlings developed from seeds treated with a 0.0001% aqueous solution of the SA-IBA complex exhibited more intensive development and formation of vegetative organs, particularly shoots and leaves, compared with the control treatment. In biological tests, the effect of 0.0001% aqueous solutions of salicylic compounds on the growth parameters of tomato seedlings was evaluated in comparison with a control group. The results showed that the compounds under study exerted varying degrees of positive influence on the length of both the root and the aerial parts. The potential plant growth-stimulating properties of the synthesized compounds were assessed based on seed germination and early seedling development indicators.

Conclusion

Thus, the findings from the investigation of salicylic acid salts and ion-pair complexes can be summarized as follows:

1. Ion-pair complexes of SA with sodium and potassium salts, TEA and IBA were successfully synthesized. Their structural properties were characterized using FT-IR and $^{1}H/^{13}C$ NMR spectroscopy. Furthermore, their thermal stability and decomposition profiles were evaluated via TGA/DTG, while key physicochemical parameters were determined using standard analytical techniques.
2. The effects of 0.0001% aqueous solutions of SA salts and ion-pair complexes on tomato seed germination and early seedling development were systematically evaluated. High germination rates were observed across all treatments, reaching 100% for the SA-IBA complex and SA sodium salt, and 97% for the SA-TEA complex and SA potassium salt. Regarding elongation growth, the maximum increase in shoot length (15.6% relative to the control) was recorded in seedlings treated with the SA-TEA complex and SA sodium salt, whereas the SA-IBA complex and SA potassium salt induced a 9.4% increase. Notably, root elongation was most pronounced under SA-IBA complex treatment, showing a 27.0% increase compared to the control. Root length enhancements for the remaining treatments followed the order: SA TEA complex (23.8%), SA potassium salt (19.1%), and SA sodium salt (14.3%). Overall, these results demonstrate that low-concentration (0.0001%) SA salts and ion-pair complexes exert a

significant stimulatory effect on tomato seed germination and early seedling growth parameters, highlighting their potential application as plant growth promoters.

Conflict of interest

The authors announced that there are no conflicts of interest regarding this current work.

References

1. Pigolev A.V., Degtyrarev E.A., Miroshichenko D.N., Savchenko T.V. Prospects for the application of jasmonates, salicylates, and abscisic acid in agriculture to improve plant stress resistance (review). *Agricultural Biology*, 2023, **Vol. 58(1)**, p. 3-22. DOI:10.15389/agrobiology.2023.1.3eng
2. Vlot A.C., Dempsey D.A., Klessing D.F. Salicylic acid, a multifaceted hormone to combat disease. *Annual review of phytopathology*, 2009, **Vol. 47**, p. 177-206. DOI:10.1146/annurev.phyto.050908.135202
3. Raskin I. Role of Salicylic acid in plants. Annual Review of plant physiology and plant molecular biology, 1992, **Vol. 43,** p. 439-463. DOI:10.1146/annurev.pp.43.060192.002255
4. Fonseca Miguel J. Influence of sodium salicylate on adventitious organogenesis of a commercial cucumber cultivar. *Multidisciplinary Science Journal*, 2023, **Vol. 5(1),** Article e2023006. DOI:10.31893/multiscience.2023006
5. Rasulov Ch.K., Movsumova A.Kh., Rustamov S.T., Haydarli G.Z., Bagirzade R.Z., Farzalieva A.H. Cycloalkylation reactions of ortho-chlorophenol with 1(3)-methylcyclohexenes in the presence of KU-23 catalyst. *Processes of Petrochemistry and Oil Refinin*g, 2026, **Vol. 27(1)**, p. 199-208. DOI: 10.62972/1726-4685.2026.1.199
6. Rasulov Ch.K., Hasanov A.A., Hasanova G.J., Haydarli G.Z., Rustamov S.T. Polyphenols: General concepts and biological activity. *Processes of Petrochemistry and Oil Refining*, 2024, **Vol. 25(4)**, p. 1090-1107. DOI: 10.62972/1726-4685.2024.4.1090
7. Clarke S.M., Mur L.A.J., Wood J.E., Scott I.M. Salicylic acid-dependent signaling promotes basal thermotolerance but is not essential for acquired thermotolerance in arabidopsis thaliana. *The plant journal*, 2004, **Vol. 38(3)**, p. 432-447. DOI: 10.1111/j.1365-313X.2004.02054.x
8. Dat J.F., Lopez-Delgado H., Foyer C.H., Scott I.M. Parallel changes in H_2O_2 and catalase during thermotolerance induced by salicylic acid or heat acclimation in mustard seedlings. *Plant Physiology,* 1998, **Vol. 116(4)**, p. 1351–1357. DOI: 10.1104/pp.116.4.1351
9. Kumar R.R., Sharma S.K., Goswami S., Verma P., Singh K., Dixit N., Pathak H., Viswanathan C., Rai R.D. Salicylic acid alleviates heat stress-induced oxidative damage of the starch biosynthesis pathway by modulating the expression of heat-stable genes and proteins in wheat (triticum aestivum). *Journal of Plant Physiology*, 2015, **Vol. 37(8)**, p. 1-12. DOI: 10.1007/s11738-015-1899-3
10. Hayat S., Ali B., Ahmad A. Salicylic Acid: Biosynthesis, Metabolism and Physiological Role in Plants. Salicylic Acid: A Plant Hormone. *Springer*, Dordrecht, 2007, pp. 1–14. DOI: 10.1007/1-4020-5184-0_1
11. Kang H.M., Saltveit M.E. Chilling Tolerance of Maize. Cucumber and rice seedling leaves and roots are differentially affected by salicylic acid. *Physiologia Plantarum,* 2002, **Vol. 115(4)**, p. 571-576. DOI: 10.1034/j.1399-3054.2002.1150411.x
12. Amrahov N.R., Gasimov R.J., Bayramov M.A., Omarova S.N., Aliyeva G.S., Mammadova R.B., Balayeva O.O., Mammadov Z.M. Influence of dinitrosalicylic acid on the protective system of cotton seedlings (Gossypium hirsutum L.). *Advances in Biology Earth Sciences*, 2024, **Vol. 9(1)**, p. 111-123. DOI: 10.62476/abes9111
13. Asadova R.A., Bagirzade R.Z. Synthesis and application of new plant growth stimulants based on petroleum acid salts: The case of ornamental plants. *Bulletin of Baku State University*, 2024, **Vol. 29,** p. 328-333.

14. Asadova R.A., Abbasov V.M., Nasirov F.A., Farzaliyeva A.G., Novruzova A.I. Environmentally Friendly Polysaccharide Chitosan as a Biologically Active Substance: Effect on Seeds of Eldarian Pine (Pinus eldarica). *Processes of Petrochemistry and Oil Refining*, 2026, **Vol. 27(3)**, p. 1070-1076. DOI: 10.62972/1726-4685.2026.3.1070
15. Abbasov V.M., Ismayilov I.T., Asadova R.A., Allahverdiyev E.I., Nabiyev R.J. Study of the Effect of Organic Acid Salts on the Germination of Tomato Seeds and the Formation of Green Biomass in Seedlings. *Processes of Petrochemistry and Oil Refining*. 2021, **Vol. 22(1)**, p. 117-125
16. Abbasov V.M., Bagirzade R.Z., Asadova R.A. Compositions of succinic acid salts as plant growth stimulants. *Proceedings of the Republican International Scientific Conference of the Y.H. Mammadaliyev Institute of Petrochemical Processes*, 2024, p. 242-245.
17. Alikhanova A.I., Mamedova A.F., Ibadov E.A., Nurullayeva D.R. Preparation and study of copolymer of N,N′-(p-phenylene)bismaleimide with allyl ester of salicylic acid. *Chemical Problems*, 2023, **Vol. 21(4)**, p. 361-369. DOI: 10.32737/2221-8688-2023-4-361-369
18. Fatullayeva P.A. Complexes of metals with hydrazone hydrazide salicylic acid. *Chemical Problems,* 2021, **Vol. 19(2)**, p. 79-83. DOI:10.32737/2221-8688-2021-2-79-83
19. Gondolova G.H., Medjidov A.A., Fatullayeva P.A., Israfilov A.I. Synthesis and spectroscopic characterization of Fe(III), Mn(II) and Cu(II) complexes with N′-maleoil-salicylic-hydrazid. *Chemical Problems*, 2018, **Vol. 16(1)**, p. 44-50.
20. Hayat Q., Hayat S., Irfan M., Ahmad A. Effect of exogenous salicylic acid under changing environment: A review. *Environmental and Experimental Botany*, 2010, **Vol. 68(1)**, p. 14-25. DOI: 10.1016/j.envexpbot.2009.08.005
21. Hayat S., Fariduddin Q., Ali B., Ahmad A. Effect of salicylic acid on growth and enzyme activities of wheat seedlings. *Acta Agronomica Hungarica*, 2005, **Vol. 53(4)**, p. 433-437. DOI: 10.1556/AAgr.53.2005.4.9