REPUBLIC OF AZERBAIJAN

On the rights of the manuscript

ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

SYNTHESIS OF NOVEL SUPRAMOLECULAR ENSEMBLES BASED ON GRAPHENE OXIDE AND HETEROCYCLIC COMPOUNDS AND THEIR INVESTIGATION

Speciality:	2306.01 – Organic chemistry
Field of science:	Chemistry
Applicant:	**Alakbar Elman Huseynzada**

Baku – 2025

The work was performed at the Department of Organic Chemistry of Baku State University.

Scientific supervisors: doctor of chemical sciences, academician
Abel Mamedali Maharramov

doctor of chemical sciences,
associate professor
Ulviyya Alimammad Hasanova

Official opponents: doctor of chemical sciences, professor
Elman Idris Mammadov

doctor of chemical sciences, professor
Gulahmad Mirahmad Talibov

doctor of chemical sciences,
associate professor
Omar Abdurahim Sadıgov

Dissertation council ED 2.16 of of Supreme Attestation Commission under the President of the Republic of Azerbaijan operating at Baku State University

Chairman of the Dissertation council:
doctor of chemical sciences, professor
Ibrahim Garib Mammadov

Scientific secretary of the Dissertation council:
doctor of chemical sciences,
associate professor
Farid Nadir Naghiyev

Chairman of the scientific seminar:
doctor of chemical sciences
Khammed Asad Asadov

GENERAL CHARACTERISTICS OF THE WORK

Relevance of the topic and the degree of elaboration. Supramolecular chemistry, which was singled out as a separate field of chemistry by Nobel laureate Jean-Marie Lehn in 1978, is a relatively young field of science, which, due to its popularity, attracts scientific minds to its ranks, contributing to its rapid development. This is also supported by numerous Nobel Prizes in this field, which further contributed to the expansion of the field of popularity by switching the attention of scientists around the world to it. The reason for the great popularity of supramolecular chemistry is that the assemblies that are the objects of its research have a very wide range of application, in particular, sensor technology, molecular electronics (molecular computers and switches, transistors and molecular wires), photochemical and magnetic molecular devices, catalysis, drug design, etc. Such a wide range of application is associated with the structure of the ensemble itself, the "building blocks" (tectons) of which are the receptor and the substrate. By changing the receptor and the substrate, it is possible to obtain an ensemble with specified properties. Molecules of various substances can be used as substrates and receptors, which, in principle, determines the wide range of application of the ensemble.

One of the components that can be widely used as a substrate are dihydropyrimidines. The most widespread method for obtaining these heterocycles is the three-component Biginelli reaction, discovered in 1893 by the Italian scientist Pietro Biginelli. Despite the fact that these substances have been known for a long time, the chemistry of these compounds is increasingly enriched every year. The reason for this is the wide range of application of dihydropyrimidines, the most famous of which is drug design. It was found that this class of compounds demonstrates such activities as anticancer, antituberculosis, antibacterial, antiviral, analgesic, proliferative, antifungal, mixed, blockers of calcium and potassium channels, etc. However, as is known, a substance showing activity at the early stages of research, subsequently, due to various factors, may lose the chance to become a drug. The peculiarity of dihydropyrimidines is that various drugs have already been synthesized on their basis, such as monastrol, enastron, fluorastrol, mon-97 (anti-cancer activity), batzeladine A and B (anti-HIV activity). Considering the exceptional importance of dihydropyrimidines in medicine, various methods for transforming dihydropyrimidine frameworks are also being developed, among which the oxidation reaction occupies a special place. The importance of the oxidation reaction is due to the fact that the solubility of the oxidized products in polar solvents is higher. In addition, the introduction of various functional groups is simplified, as well as the formation of new C–C, S–S and other types of bonds, which leads to an expansion of the scope of application of dihydropyrimidines. In addition, in some cases, the oxidized dihydropyrimidine is more biologically active than the original. Based on the above, the search for new highly effective methods for the synthesis of dihydropyrimidines and their oxidation, as well as the study of the crystal structure of the obtained substances and intermolecular interactions is one of the urgent tasks facing scientists[1].

Another tecton of the ensemble that can be widely used as a receptor is graphene oxide nanolayers. It is a single-layer sheet of graphite oxide and has various oxygen-containing groups: hydroxyl, epoxy, carboxyl, carbonyl, lactone and quinone groups. These groups can easily participate in various non-covalent interactions, which makes graphene oxide nanolayers a valuable tecton for receiving of ensemble. As for the properties of graphene oxide and its possible applications, it has proven to be a unique material. It has been established that graphene oxide has diverse applications, in particular, it can be used as a drug carrier, electrodes, gas sensors, biosensors, sensors (in conjunction with a DNA molecule), catalysts, adsorbents, etc. [2].

Thus, it follows from the above that the search for original methods of synthesis and oxidation of new dihydropyrimidines, the study of the crystal structure and intermolecular interactions of the obtained products, the production of new supramolecular assemblies by conjugating them with graphene oxide and further study of their biological activity using both experimental and computational methods, is undoubtedly

---

[1] Kappe, C.O. Recent advances in the Biginelli dihydropyrimidine synthesis. New tricks from an old dog // Accounts of Chemical Research, – 2000. v. 33, № 12, – pp. 879-888.

[2] Chung, C. Biomedical applications of graphene and graphene oxide / C.Chung, Y.K.Kim, D.Shin [et al.] // Accounts of Chemical Research, – 2012. v. 46, № 10, – pp. 2211-2224.

very relevant and interesting, both from the standpoint of theoretical organic and supramolecular chemistry, and from an applied point of view.

Object and subject of research. The object of the study is new supramolecular assemblies based on dihydropyrimidines conjugated with graphene oxide. The subject of the research is the investigation of the synthesis of dihydropyrimidines and their oxidation products, the study of the crystal structure and intermolecular bonds of the mentioned dihydropyrimidine derivatives, as well as the study of the process of conjugation of graphene oxide with dihydropyrimidines.

Goals and tasks of the study. *The main goal* of the dissertation is the synthesis of supramolecular assemblies based on graphene oxide nanolayers conjugated with dihydropyrimidines, the study of the conjugation process and the investigation of the biological activity of the resulting novel assemblies (in comparison with tectons).

To achieve this goal, the following *tasks* were performed:

- Synthesis of various dihydropyrimidines in the presence of copper triflate and cerium chloride under microwave conditions;
- Investigation of the influence of copper triflate on the process of obtaining dihydropyrimidines based on salicylic aldehyde derivatives;
- Regioselective oxidation of dihydropyrimidines in the presence of ceric ammonium nitrate;
- X-ray diffraction investigation of single crystals of synthesized dihydropyrimidine derivatives, study of the conformation of the dihydropyrimidine ring and the effect of hydrogen bonds on the stability of the tautomer;
- Investigation of intermolecular interactions of synthesized dihydropyrimidines by the Hirshfeld surface analysis method;
- Synthesis of graphene oxide nanolayers by a modified Hammer method;
- Synthesis of graphene oxide-dihydropyrimidine-based ensembles and investigation of the conjugation process;
- Investigation of biological activity of obtained dihydropyrimidines and ensembles against gram-positive and gram-negative bacteria, fungi, cancer cell lines and parasites using experimental and computational methods

Research methods. The research was performed at the Department of Organic Chemistry of Baku State University. The following devices and appliances were used for the research:

- NMR investigations – BRUKER FT AVANCE 300;
- Mass investigations – Agilent 6530 Q-TOF LC-MS;
- IR investigations – Bruker Tensor II FTIR;
- XRD investigations of single crystals – Bruker APEX II;
- XRD investigations of powders – Rigaku Mini Flex 600;
- SEM investigations – JEOL JSM-7600F;
- Microwave reactor – CEM Discover™ System;
- MPLC – Biotage Isolera;
- Elemental analyzer – Carlo Erba 1108;
- MP – Buchi B-540.

The main states submitted for defense.

- Development of an effective method for the synthesis of dihydropyrimidines by the Biginelli reaction in the presence of copper triflate and cerium chloride under microwave conditions;
- Regioselective oxidation of dihydropyrimidines catalyzed by cerium ammonium nitrate;
- Determination of non-covalent interactions in dihydropyrimidine crystals by X-ray diffraction, their influence on crystal packing, conformation of the dihydropyrimidine ring and on the stability of tautomers of oxidation products;
- Investigation of intermolecular interactions of synthesized dihydropyrimidines by the Hirshfeld surface analysis method;
- Synthesis of graphene oxide nanolayers modified by the Hammer method;
- Synthesis and investigations of ensembles based on graphene oxide and dihydropyrimidines;
- Investigation of biological activity of obtained dihydropyrimidines and ensembles against gram-positive and gram-negative bacteria, fungi, cancer cell lines and parasites using experimental and computational methods.

Scientific novelty of the work. For the first time, new supramolecular assemblies based on graphene oxide and dihydropyrimidines were synthesized and investigated. Dihydropyrimidines (both new and known) were obtained by a modified method under microwave conditions in the presence of copper triflate and cerium chloride. In addition, for the first time, the effect of copper triflate on the Biginelli reaction in the presence of salicylic aldehyde derivatives was studied and the formation of only the dihydropyrimidine ring under the above conditions, rather than the oxygen-containing tricyclic derivative, was proven. In addition, novel dihydropyrimidines were also obtained in the presence of cerium ammonium nitrate by regioselective oxidation using our modified method. X-ray diffraction studies of the obtained single crystals allowed us to draw conclusions about the presence of intermolecular interactions, their role in the crystal packing and the tautomeric process. Intermolecular interactions were also studied by the Hirshfeld surface analysis method and their "fingerprints" were shown. Conformations of dihydropyrimidine rings were also studied by the single X-ray diffraction method. The resulting ensembles received on the basis of graphene oxide and dihydropyrimidines were tested against various bacteria, fungi, cancer cell lines and parasites using experimental and computational methods. The results of biological activity revealed that some representatives exhibit higher activity compared to antibiotics.

Theoretical and practical significance of the research. The practical value of the work is that novel dihydropyrimidines and ensembles based on them were obtained, possessing biological activity against gram-positive and gram-negative bacteria, fungi, cancer cell lines and parasites, which in some representatives is higher than that of known antibiotics. The theoretical value of the work is that methods for the synthesis and oxidation of dihydropyrimidines were developed, the effect of the catalyst in the Biginelli reaction in the presence of salicylic aldehyde derivatives was studied, intermolecular interactions and their effect on crystal packing, tautomerism and ring conformation were investigated, the process of conjugation of dihydropyrimidines with graphene oxide was explored.

Aprobation and application. The results of the dissertation were presented at various local and international conferences:

– 6th Rostocker International Conference: «Thermophysical Properties for Technical Thermodynamics» (Germany, 2017);

- 7th Rostocker International Conference: «Thermophysical Properties for Technical Thermodynamics» (Germany, 2018);
- II International Scientific Conference of Young Scientists (Azerbaijan, 2018);
- 10th Rostocker International Conference: «Thermophysical Properties for Technical Thermodynamics» (Germany, 2021).

The main results of the dissertation were published in 14 scientific papers, including 9 articles and 5 conference materials. The results obtained contributed to the enrichment of the chemistry of dihydropyrimidines, as well as assemblies based on them. In addition, the obtained results of in vitro biological activity create the basis for the synthesized assemblies and individual molecules to move to the next stage of research - in vivo biological studies.

Name of the organization where the dissertation work was performed. The dissertation work was carried out at the Department of Organic Chemistry of the Baku State University.

The total volume of the dissertation in characters with an indication of the volume of its structural sections separately. The dissertation consists of an introduction, three chapters (literature review, discussion of results, experimental part), conclusion, list of used literature and appendix, which are written on 302 pages of A4 format. The main part of the work (excluding figures, tables, graphs and list of references) is 218084 characters. The list of used literature includes 168 sources, which are cited in the dissertation. In addition to this, the dissertation contains 22 schemes, 32 tables and 73 figures.

The introduction (12531 characters) provides general information about the dissertation.

The literature review (37301 characters) provides information on supramolecular assemblies and their tectons. The methods of synthesis and oxidation of dihydropyrimidines, methods of studying their structures, biological activity, methods of synthesis of graphene oxide and assemblies based on it are considered, and literature information on the areas of their application is also provided.

The second chapter (109096 characters) includes the synthesis of dihydropyrimidines in the presence of copper triflate and cerium chloride, the study of the effect of copper triflate on the Biginelli reaction in the presence of salicylic aldehyde derivatives, the study of the structure, conformation and non-covalent interactions by X-ray diffraction and Hirshfeld surface analysis, the study of the process of ensemble formation. In addition, it also describes the biological activity of the synthesized compounds and ensembles by both experimental and computational methods.

The third chapter (57505 characters) describes the methods of synthesis, physical, chemical and spectral characteristics of the obtained tectons and ensembles, as well as methods for conducting various studies.

The conclusions (1651 characters) demonstrate the main findings of the dissertation.

The appendices contain NMR, mass, IR spectra and some crystallographic data.

Personal contribution of the author. The author took direct part in the implementation of the dissertation work by solving the tasks set. The applicant took an active part in compiling a literature review based on the latest research in the specified area in the world literature, in conducting experiments and in analyzing the spectra of reaction products. The generalization of ideas and results was carried out with the direct participation of specialists in the relevant fields (organic chemists, biologists, etc.) during writing articles.

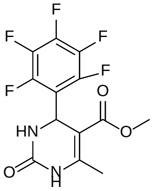
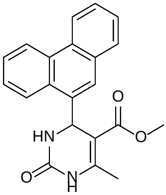
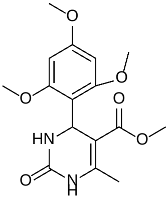
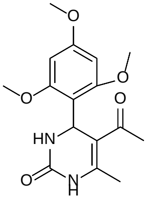
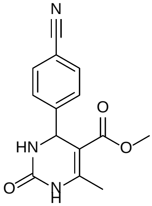
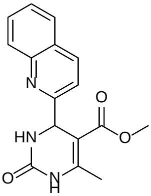
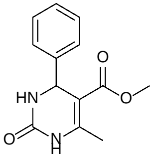
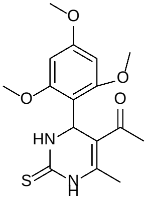
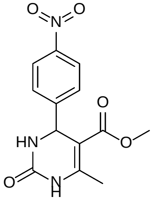
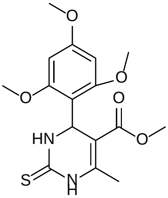
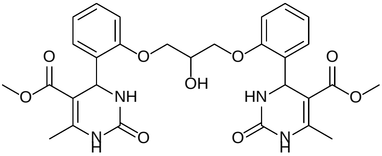
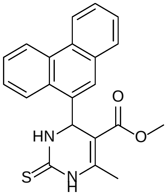
MAIN CONTENT OF THE WORK

The main objective of the dissertation is to obtain novel assemblies based on graphene oxide nanolayers modified with dihydropyrimidine derivatives and to investigate them. The studies include not only the investigation of obtained novel assemblies, but also individual components of the assemblies. The structures of the target products themselves were studied using NMR spectroscopy, mass spectrometry, elemental analysis, and X-ray diffraction analysis (single crystals), which made it possible to detect intermolecular and intramolecular interactions in the crystal lattice of the molecules under study and to investigate their effect on the conformation of the dihydropyrimidine ring, as well as to identify the pattern of existence of tautomers in crystalline form. Intermolecular interactions were also studied by the Hirshfeld surface analysis method and their "fingerprints" were shown. Graphene oxide nanolayers, as well as assemblies based on them, were studied by SEM and IR methods, as well as X-ray structural analysis (powders) and the sizes of the nanolayers and their morphology were studied. In addition, biological activities of both dihydropyrimidine derivatives and assemblies based on them were studied. Furthermore, computational studies were carried out using the Gaussian software, which made it possible to calculate various quantum-chemical parameters, theoretical NMR and IR spectra. Optimization was carried out and molecular electrostatic potential (MEP) maps were created, which in turn made it possible to determine the active centers of the studied compounds. Using the Maestro software with the use of various modules, it was possible to explain the high biological activity of a particular sample by determining the target proteins with which the docking of the studied molecules occurs. In addition to the above, ADME/T analysis was also performed to test the drug-likeness of the analyzed compound. Let us consider each of the investigations in more detail.

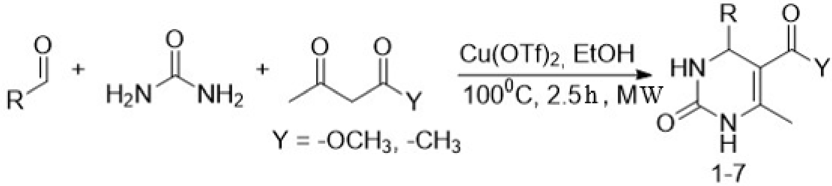
1.1. Synthesis and investigations of dihydropyrimidine derivatives

1.1.1. Synthesis of dihydropyrimidine derivatives. As is known, the most common method for synthesizing dihydropyrimidines is a three-component reaction, which was discovered by the Italian scientist Pietro Biginelli in 1893 and named after him. At the initial stage of the synthesis, only one of the "building blocks" was changed - it was aldehyde. The aldehydes used were 2,3,4,5,6-pentafluorobenzaldehyde, 2,4, 6-trimethoxybenzaldehyde, 4-cyanobenzaldehyde, benzaldehyde, 4-nitrobenzaldehyde, 2,2'-((2-hydroxypropane-1,3-diyl)-bis(oxy))dibenzaldehyde and phenanthrene-9-carbaldehyde. The other two "building blocks" in reactions with the above aldehydes were methyl acetoacetate and urea. Various types of catalysts have been investigated, such as iodine under microwave conditions, $Yb(PFO)_3$, TMSCl/CAN, [Hmim] HSO_4-$NaNO_3$, CAN, GaI_3, HBF_4-SiO_2, $Sm(ClO_4)_3$, $H_3PMo_{12}O_{40}$, $La(OTf)_3$, $Sc(OTf)_3$, In(OTf), $RuCl_3$, $MgCl_2\times6H_2O$, $CeCl_3\times7H_2O$, trifluoroacetic acid, monochloroacetic acid, acetic acid and ammonium chloride, but all of them were not fully effective and did not allow the Biginelli reaction to be carried out on the basis of all used aldehyde frameworks, urea and methyl acetoacetate. Only by carrying out the reaction in the presence of copper (II) salt of trifluoromethanesulfonic acid under microwave conditions it was possible to obtain the target dihydropyrimidines 1-7 (Scheme 1, Table 1). In addition to the fact that

Table 1. Dihydropyrimidines synthesized by the Biginelli reaction

№	Product	Yield, %	№	Product	Yield, %
1		56	7		54
2		74	8		80
3		74	9		61.1
4		79	10		63
5		72	11		67
6		60	12		68

the mentioned catalyst made it possible to obtain a series of dihydropyrimidines under the same conditions, other positive aspects of this method are:



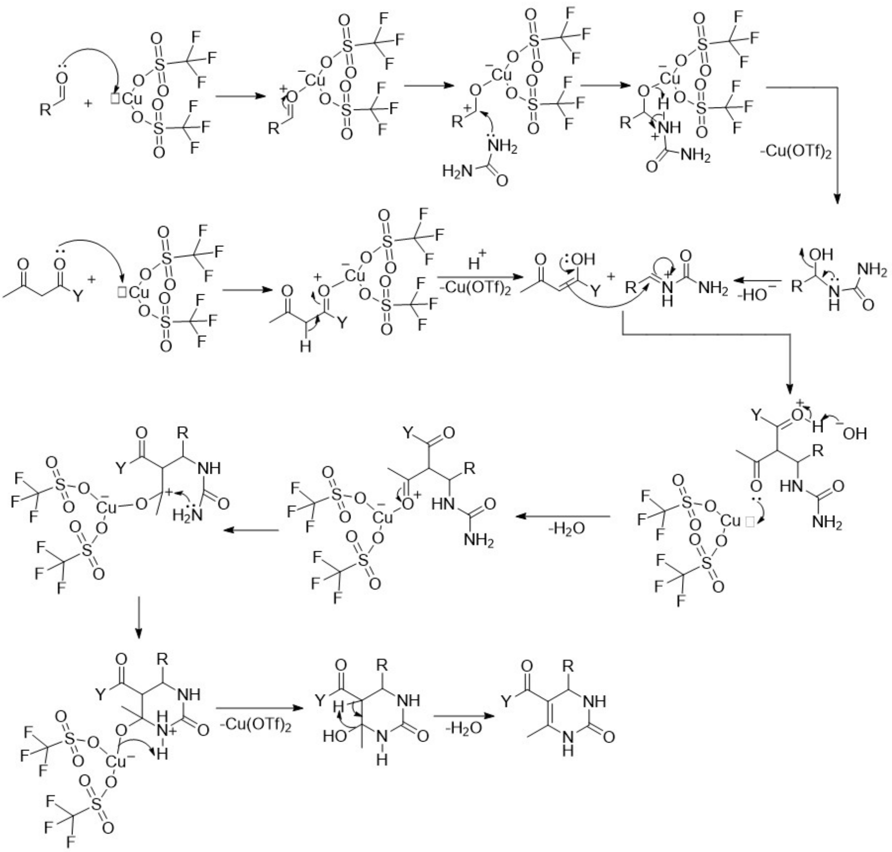
Scheme 1. Synthesis of dihydropyrimidines

- Short reaction time (2,5 h).
- Almost complete absence of the stage of purification of the obtained target products (1-7) – the precipitate obtained during the reaction was simply washed with several milliliters of distilled water.
- The method partially satisfies the principles of “green chemistry” due to the fact that, firstly, there is no procedure for purifying the obtained target products – from which one can conclude that there is no need to dispose of organic solvents used in purification. The second reason is that copper (II) salt of trifluoromethanesulfonic acid is a low-toxic and cheap raw material. The third reason – is the possibility of reusing the catalyst. The conducted studies revealed that even after five times use of the catalyst, no noticeable change in the yields of products was observed (the decrease in yield was 1-3%).

Single crystals of compounds 2,3 (despite the fact that this dihydropyrimidine is a substance known in the literature, its X-ray structural studies have not been described in the literature) and 7 were also obtained, the X-ray structural studies of which are described below.

The proposed mechanism of the Biginelli reaction in the presence of copper triflate is shown in Scheme 2.

If acetylacetone will be used as the methylene active compound instead of methyl acetoacetate, then according to the studies, the concentration of the catalyst must be three times less to obtain the target dihydropyrimidine compared to the primary method of synthesizing dihydropyrimidines based on methyl acetoacetate indicated in the experimental section. The Biginelli reaction was carried out in the presence of

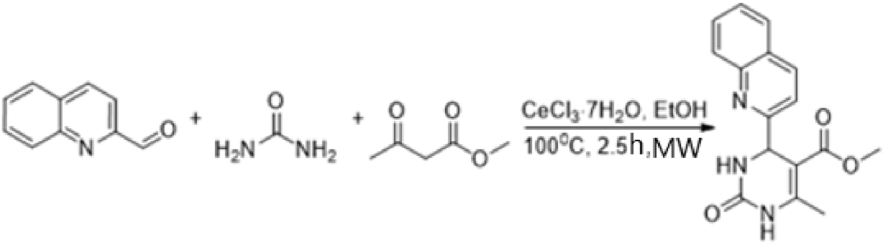


Scheme 2. Proposed mechanism of the Biginelli reaction in the presence of copper triflate

2,4,6-trimethoxybenzaldehyde and urea, and a new dihydropyrimidine 8 was obtained with a yield of 80% (Table 1). A single crystal of compound 8 was also obtained, the X-ray structural studies of which are described below. The reason why, when using acetylacetone, the concentration of the catalyst is taken three times less compared to methyl acetoacetate, is due to the fact that acetylacetone is a stronger CH-Bronsted acid, which contributes to the fact that it more easily enters into the Biginelli reaction and, accordingly, less catalyst is required (milder conditions).

It was also interesting to test the effect of copper (II) salt of trifluoromethanesulfonic acid on the Biginelli reaction in the presence of heteroaromatic aldehydes. Quinoline-2-carbaldehyde was used as the heteroaromatic aldehyde, and urea and methyl acetoacetate were used as the remaining "building blocks". However, even with 0.1 μg of catalyst, the reaction did not lead to the desired dihydropyrimidine. At the end of the reaction time, a black oily liquid was formed at the bottom of the flask. Reducing the reaction time even to 10 minutes also led to the formation of a black liquid, while reducing the reaction time to one minute only contributed to the blackening of the reaction solution. Mass spectrometric studies of the reaction mixture showed the formation of a polymer based on quinoline-2-carbaldehyde under the above conditions. The reaction was also unsuccessful with catalysts such as iodine under microwave conditions, $Yb(PFO)_3$, TMSCl/CAN, $[Hmim]HSO_4$-$NaNO_3$, CAN, GaI_3, HBF_4-SiO_2, $Sm(ClO_4)_3$, $H_3PMo_{12}O_{40}$, $La(OTf)_3$, $Sc(OTf)_3$, $In(OTf)_3$, $RuCl_3$, $MgCl_2 \times 6H_2O$, $InCl_3$, $InBr_3$, CF_3COOH, $Yb(OTf)_3$, $YbCl_3$, HCl, monochloroacetic acid, acetic acid and ammonium chloride.

Only by carrying out the reaction under microwave conditions in the presence of cerium III chloride heptahydrate did it become possible to obtain the target new dihydropyrimidine 9 with a yield of 61.1% (Scheme 3, Table 1). A single crystal of compound 9 was also obtained, the X-ray structural studies of which are described below[3]. It is assumed that the mechanism of the Biginelli reaction in the presence of cerium III chloride will occur similarly to Scheme 2.

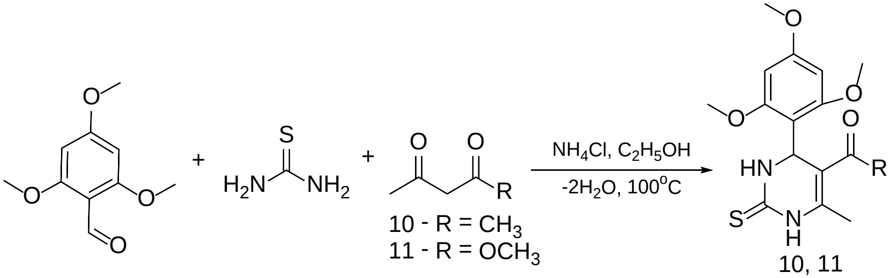


Scheme 3. Synthesis of dihydropyrimidine 9

---

[3] Huseynzada, A.E. Synthesis, crystal structure and antibacterial properties of 6-methyl-2-oxo-4-(quinolin-2-yl)-1,2,3,4-tetrahydropyrimidine-5 carboxylate / A.E.Huseynzada, C. Jelsch, H.N.Akhundzada [et al.] // Journal of Molecular Structure, – 2020. v. 1219, – p. 128581-1-21.

When the third "building block" – urea – was replaced by thiourea (2,4,6-trimethoxybenzaldehyde and 9-phenanthrenecarboxaldehyde were used as aldehydes, and acetylacetone and methyl acetoacetate were used as the methylene active compound), copper(II) salt of trifluoromethanesulfonic acid also turned out to be ineffective. New thio derivatives of 2,4,6-trimethoxybenzaldehyde 10 and 11 were synthesized in the presence of ammonium chloride with yields of 63 and 67%, respectively (Scheme 4, Table 1).



Scheme 4. Synthesis of dihydropyrimidines 10 and 11

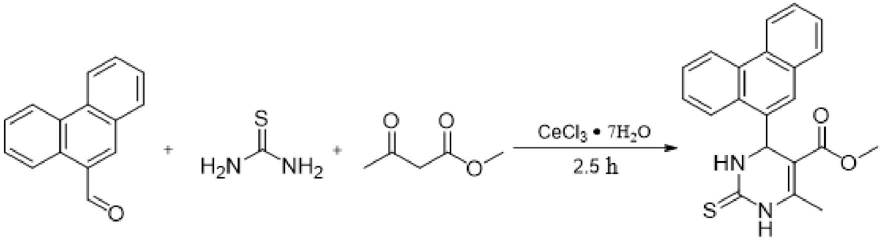
Similar to compounds 2 and 8, the synthesis of dihydropyrimidine 12 used more ammonium chloride (1.7 mg) than dihydropyrimidine 11 (1.2 mg), which was prepared from acetylacetone. Using a similar procedure for the synthesis of the new dihydropyrimidine 12 was unsuccessful. Moreover, various protocols were checked, in particular $Ce(NO_3)_3 \cdot 6H_2O$, iodine in microwave conditions, $(PhNH_3)_2$ $CuCl_4$, $[PyPS]_3PW_{12}O_{40}$ in microwave conditions, but all of them did not lead to the synthesis of the desired dihydropyrimidine. Novel dihydropyrimidine 12[4] based on 9-phenanthrenecarboxaldehyde was synthesized in the presence of cerium (III) chloride heptahydrate with a yield of 68% (Scheme 5, Table 1).

A single crystal of compound 12 was also obtained, the X-ray structural studies of which are described below.

Another interesting direction of dihydropyrimidine chemistry is the synthesis of these molecules based on salicylic aldehyde derivatives,

---

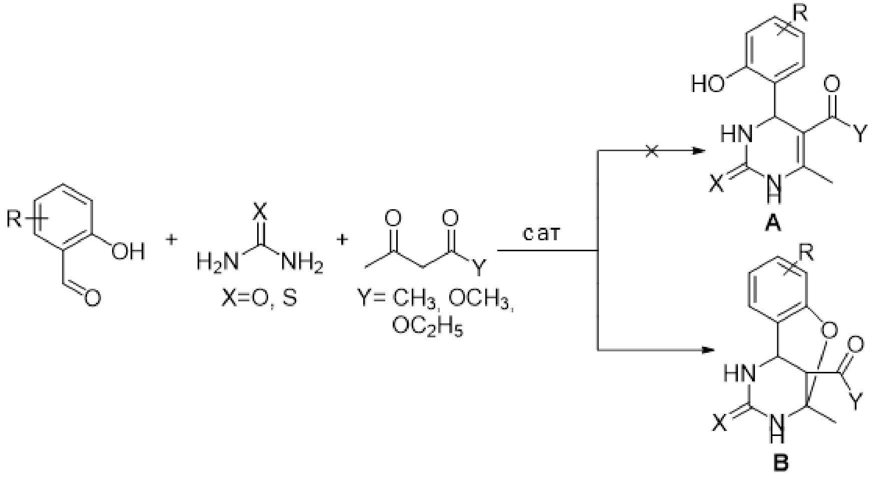
[4] Huseynzada, A. Synthesis, crystal structure, Hirshfeld surface, computational and antibacterial studies of a 9-phenanthrenecarboxaldehyde-based thiodihydropyrimidine derivative / A.Huseynzada, M.Mori, F.Meneghetti [et al.] // Journal of Molecular Structure, – 2022. v. 1267, – p. 133571-1-7.



12

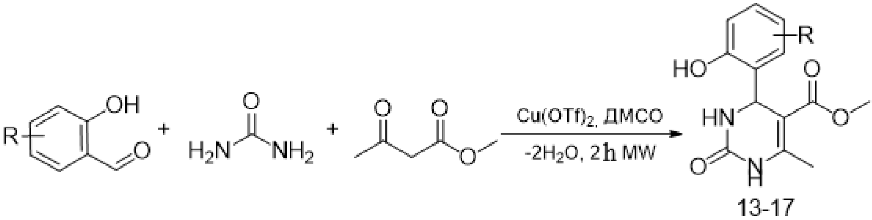
Scheme 5. Synthesis of dihydropyrimidine 12

since the presence of a phenolic hydroxyl group is very important from a medical point of view caused by the fact that this group is pharmacophoric. The chemistry of the above-mentioned groups of compounds has been studied by various groups of scientists and it has been established that under the conditions of the Biginelli reaction, two types of products can be formed. Thus, according to literature data, the condensation of salicylic aldehyde or its various derivatives, methylene active compound and urea or thiourea under the conditions of the Biginelli reaction in most cases leads to the formation of a pyran ring - an oxygen-containing tricyclic derivative of pyrimidine B instead of simple dihydropyrimidine A (Scheme 6). In this regard, it was of interest to test the



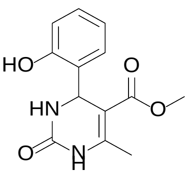
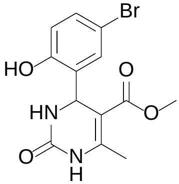
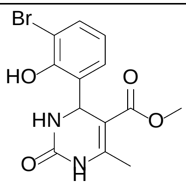
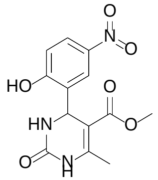
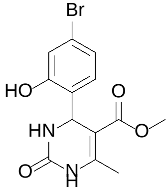
Scheme 6. Formation of dihydropyrimidine derivatives based on 2-hydroxybenzaldehydes

activity of copper (II) salt of trifluoromethanesulfonic acid in the presence of various derivatives of salicylic aldehyde. A slight modification of the original procedure allowed us to obtain various types of dihydropyrimidines 13-17, namely type A (Scheme 7, Table 2). The yields of products 13-17 varied in the range of 62-79% (Table 2). Single crystals of compounds 16 (despite the fact that this dihydropyrimidine is a known substance in the literature, its X-ray structural studies have not been described in the literature) and 17 were also obtained, the X-ray structural studies of which are described below.

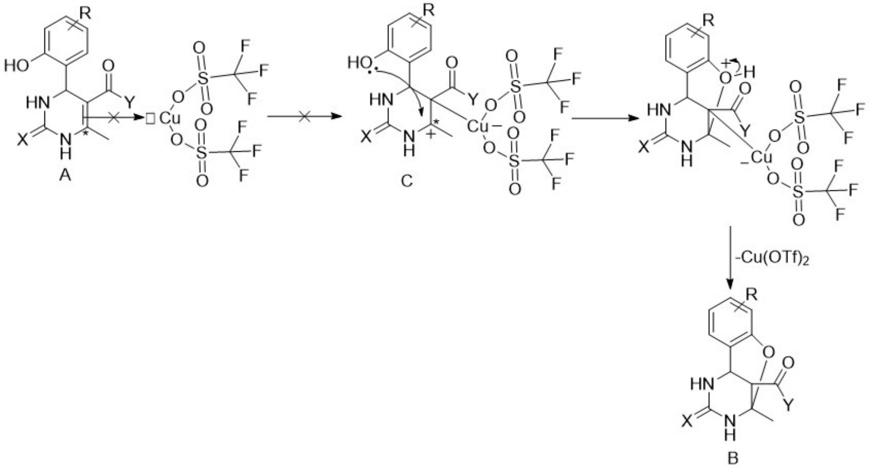


Scheme 7. Synthesis of dihydropyrimidines based on 2-hydroxybenzaldehydes in the presence of copper (II) salt of trifluoromethanesulfonic acid

Table 2. Dihydropyrimidines based on 2-hydroxybenzaldehyde derivatives

№	Product	Yield, %		Product	Yield, %
13		62	16		72
14		78	17		79
15		77			

The activity of ammonium and cerium chloride in the presence of the above-mentioned derivatives of salicylic aldehyde under Biginelli reaction conditions was also investigated. It was found that in the presence of both of the indicated catalysts, the formation of the target dihydropyrimidines **A** or **B** (Scheme 6) was not observed. The selectivity of copper (II) salt of trifluoromethanesulfonic acid in the above reaction (Scheme 7) leading to the formation of type **A** dihydropyrimidine can be clarified by considering the mechanism of formation of oxygen-containing tricyclic derivative of type **B** pyrimidine (Scheme 8). According to the Biginelli condensation mechanism, it is obvious that the formation of oxygen-containing pyrimidine of type **B** occurs through the formation of pyrimidine of type **A**. After the step of formation of molecule **A**, the double bond of the pyrimidine ring (Lewis π-base) should react with the catalyst – copper (II) salt of trifluoromethanesulfonic acid (Lewis acid) to form carbocation **C**, and this in turn will promote the attack of oxygen of the hydroxyl group of the benzene ring at the C-6 position of the dihydropyrimidine ring (*). Taking into account the bulkiness of the copper (II) salt molecule of trifluoromethanesulfonic acid, as well as the volume of the -CO-Y and –CH_3 groups, it can be assumed that such an interaction cannot occur due to the steric effect (Scheme 8). As a result, the bulkiness of the catalyst



Scheme 8. Mechanism of formation of oxygen-containing tricyclic derivative of pyrimidine type **B**

molecule and the -CO-Y and -CH_3 groups (steric effect) is the determining factor that have an impact on the selectivity of the Biginelli reaction based on 2-hydroxybenzaldehyde derivatives in the presence of copper (II) salt of trifluoromethanesulfonic acid with respect to the formation of dihydropyrimidine of type **A**. An indirect factor confirming this idea is the analysis of the literature, according to which the formation of an oxygen-containing tricyclic derivative of type **B** pyrimidine in a one-stage three-component process occurs in the presence of Arrhenius (H^+) or Lewis acids, the small size of which allows the double bond of the pyrimidine ring to react with them, followed by an attack by the oxygen of the hydroxyl group of the benzene ring at the C-6 position of the dihydropyrimidine ring (*). Thus, the small size of the catalyst promotes the formation of a tricyclic compound of type **B**[5,6]).

The next stage of the research was to carry out regioselective oxidation of dihydropyrimidines in the presence of cerium ammonium nitrate. The reason for carrying out regioselective oxidation of the dihydropyrimidine ring is, firstly, the better solubility of the oxidation products compared to the original dihydropyrimidines, which allows expanding the scope of their application. The second reason is that in some cases the biological activity of the oxidation products of dihydropyrimidines is higher than that of the unoxidized derivatives. Taking into account the above, regioselective oxidation was carried out in the presence of cerium ammonium nitrate, which made it possible to obtain oxidation products 18-26 based on dihydropyrimidines 1-8 (Scheme 9, Table 3). The yields of the regioselective oxidation products varied in the range of 1-40%[7,8]. Single crystals of compounds 19,

---

[5] Huseynzada, A.E. Crystal structure, Hirshfeld surface analysis, computational and antifungal studies of dihydropyrimidines on the basis of salicylaldehyde derivatives / A.E.Huseynzada, C.Jelsch, H.V.Akhundzada [et al.] // Journal of the Iranian Chemical Society, – 2023. v. 20, № 1, – p. 109-123.

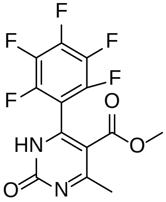
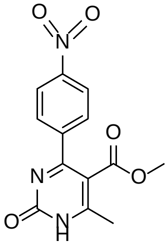
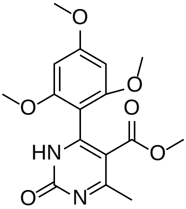
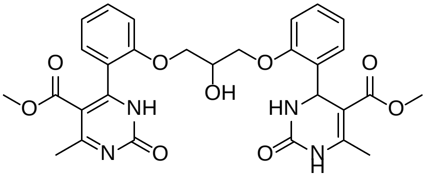
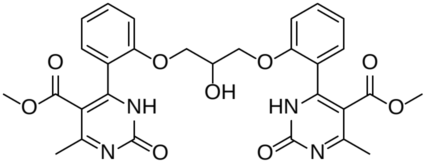
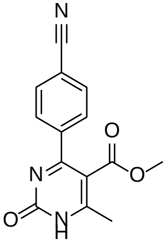
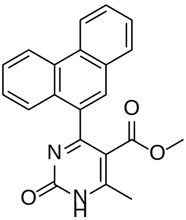
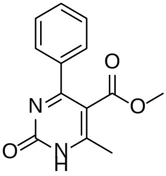
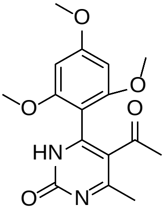
[6] Huseynzada, A.E. Synthesis, crystal structure and antibacterial studies of dihydropyrimidines and their regioselectively oxidized products / A.E.Huseynzada, C.Jelch, H.V.N. Akhundzada [et al.] // RSC Advances, – 2021. v. 11, № 11, – p. 6312-6329.

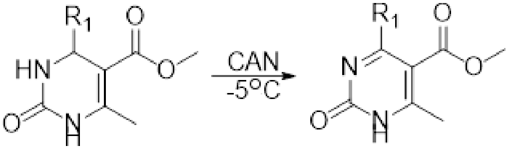
[7] Huseynzada, A. Crystal Structure, Hirshfeld Surface Analysis, In-Silico and Antimycotic Investigations of Methyl 6-methyl-4-(4-nitrophenyl)-2-oxo-1,2-dihydropyrimidine-5-carboxylate / A.Huseynzada, M.Mori, F.Meneghetti [et al.] // Crystals, – 2022. v. 13, № 1, – p. 52-72.

[8] Huseynzada, A.E. Synthesis, crystal structure and antibacterial studies of 2,4,6-trimetoxybenzaldehyde based dihydropyrimidine derivatives / A.E.Huseynzada, C.Jelsch, H.N. Akhundzada [et al.] // Journal of Molecular Structure, – 2021. v. 1241, – p. 130678-1-24.

22 and 25 were also obtained, the X-ray structural studies of which are described below.

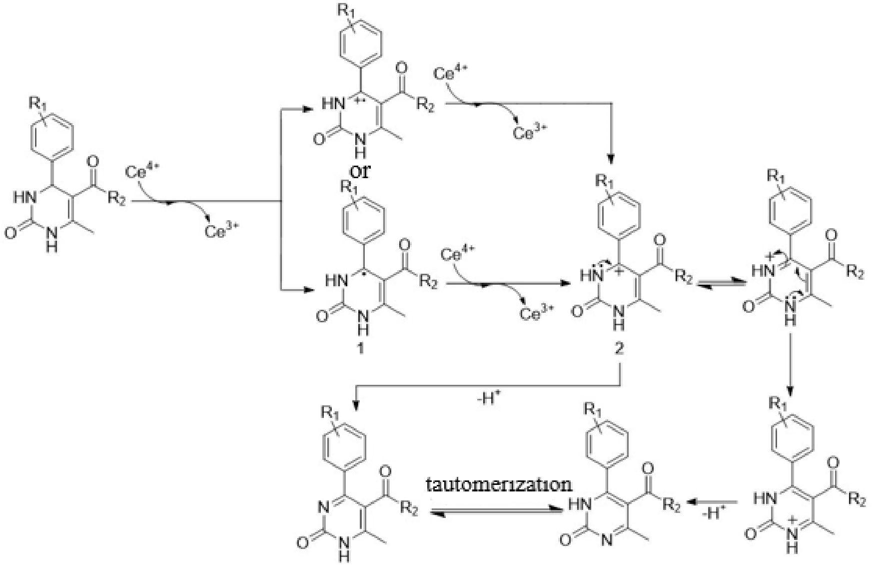
Table 3. Oxidation products of dihydropyrimidine

№	Product	Yield, %	№	Product	Yiled, %
18		1	22		28
19		40	23/24	 	15/5
20		27	25		35
21		35	26		36.4



Scheme 9. Regioselective oxidation of dihydropyrimidines

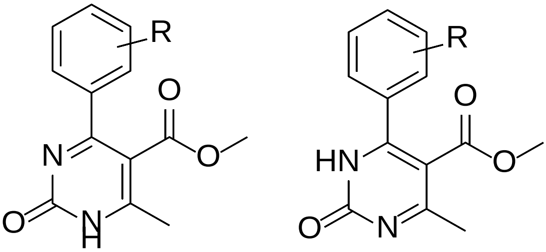
As it can be seen from Table 3, two products are obtained during oxidation of dihydropyrimidine 6: 23 (oxidation product of one dihydropyrimidine ring) with a yield of 15% and 24 (oxidation product of two dihydropyrimidine rings) with a yield of 5%. If the amount of sodium bicarbonate and cerium ammonium nitrate is taken 2 times greater than in the oxidation method specified in the experimental part, then the formation of product 23 will not be observed. In this case, the yield of product 24 increases to 22%, respectively. A further increase in the concentration of sodium bicarbonate and cerium ammonium nitrate does not significantly affect the yield of the products. Along with the above, as can be seen from Table 3, the yield of oxidized dihydropyrimidine 18 is only 1%. The reason for such a low yield of the specified compound can be explained by considering the mechanism of regioselective oxidation of dihydropyrimidines in the presence of cerium ammonium nitrate (Scheme 10). According to the mechanism of regioselective oxidation of dihydropyrimidines, the reaction is a one-electron oxidation process and carboradical **1** is formed at the first stage (another interpretation of the mechanism includes the formation of a cation-radical). In the case of compound 18, all five positions in the benzene ring are substituted by fluorine atoms, which strongly attract the electron density to themselves (strong negative induction effect), which leads to a decrease in the stability of carboradical **1** (or cation-radical), as well as the subsequently formed carbocation 2 (Scheme 10). As a result, the formation of the target product 18 occurs in a low yield. This pattern also manifests itself in the case of other oxidation products. The yield of the target oxidation products with electron-donating substituents in the aromatic ring (compounds 19, 21, 23-26) is higher than the yield of the oxidation products with electron-withdrawing substituents in the aromatic ring (compounds 20 and 22) (Table 3). This is due to the fact that the stability of the carboradical (or cation-radical), as well as the carbocation, in the case of an aromatic ring with electron-donating substituents, is higher than that of an aromatic ring with electron-withdrawing substituents.



Scheme 10. Mechanism of regioselective oxidation of dihydropyrimidines

As it can be seen from the scheme of the mechanism of regioselective oxidation of dihydropyrimidines (Scheme 10), tautomerization is characteristic for the oxidized products of dihydropyrimidines and, as a result, they can exist in solution as a mixture of two different tautomers (Scheme 11). In addition to this, it should also be noted that there are no data in the literature on the stability of tautomers. Moreover, there is also no information on the conditions under which each of the tautomeric forms exists in crystalline form. Taking into account the above, a detailed study of the oxidation products was carried out using various methods of NMR spectroscopy and X-ray structural analysis. A detailed study of the ^{1}H and ^{13}C NMR spectra showed the absence of doubling of signals, which indicates that in solution, as a result of the absence of tautomeric transitions, the above compounds exist in the form of one of the tautomers.

Further, an attempt was made to obtain single crystals of the oxidation products of dihydropyrimidines and, as indicated above, single crystals of compounds 19, 22 and 25 were obtained. According to X-ray



I II

Scheme 11. Tautomeric forms of oxidation products

structural studies, compound 19 exists in the crystal structure in the form of tautomer II, while compounds 22 and 25 are in the form of tautomer I (Figs. 1-3). As shown by X-ray structural studies of single crystals, the reason for the existence of compound 19 in the form of tautomer II is due to the presence of an intramolecular hydrogen bond between H1N and O4 of the methoxy group, which holds the hydrogen at the nitrogen atom in the N1 position and stabilizes the existence of tautomeric form II. X-ray structural study of compounds 22 and 25 did not reveal the presence of any intramolecular hydrogen bond in the structure, which makes it possible for this molecule to exist in the form of tautomer I in the crystalline form. In addition, X-ray structural analysis showed the existence of compounds 19, 22 and 25 in the form of dimers (Fig. 1-3) due to the presence of double intermolecular hydrogen bonds between the hydrogen of the N-H group and the oxygen of the carbonyl group of the pyrimidine ring. Thus, there is a hydrogen bond H1N…O1 in the case of compound 19 and H3N…O3 and H2N…O1 in the case of compounds 22 and 25, respectively (Fig. 1-3). Taking this fact into account, it can be said that the hydrogen at the nitrogen atom H1N of compound 19 takes part in the formation of both intramolecular and intermolecular hydrogen bonds that stabilize the crystal structure of the compound.

Taking into account above mentioned it can be stated that in the structure of compound 19 there is a formation of a bifurcation hydrogen bond, namely a bifurcation hydrogen bond with bifurcation donors (oxygen of the methoxy and carbonyl groups), stabilizing the formed tautomeric form II for compound 19 in the crystalline form. Moreover, taking into account all of the above, it is possible to draw a conclusion

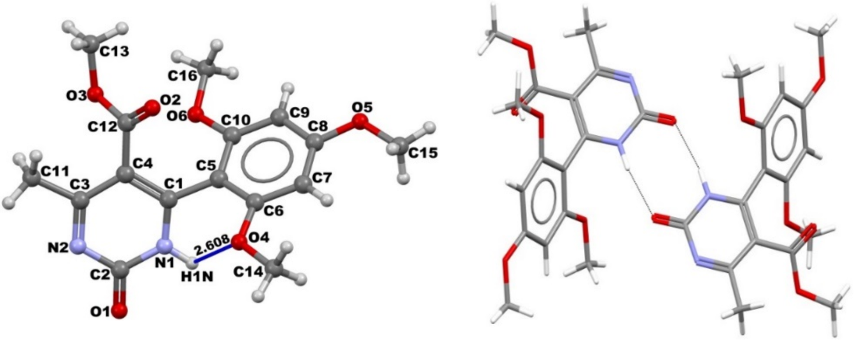


Figure 1. X-ray structure of compound 19 and the dimer formed by a double hydrogen bond

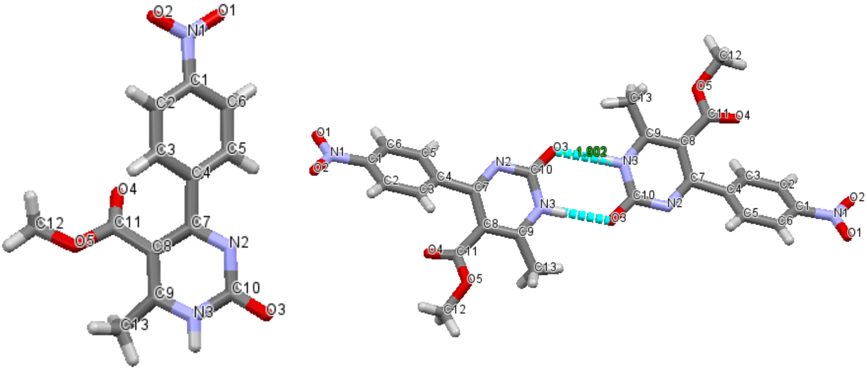


Figure 2. X-ray structure of compound 22 and the dimer formed by a double hydrogen bond

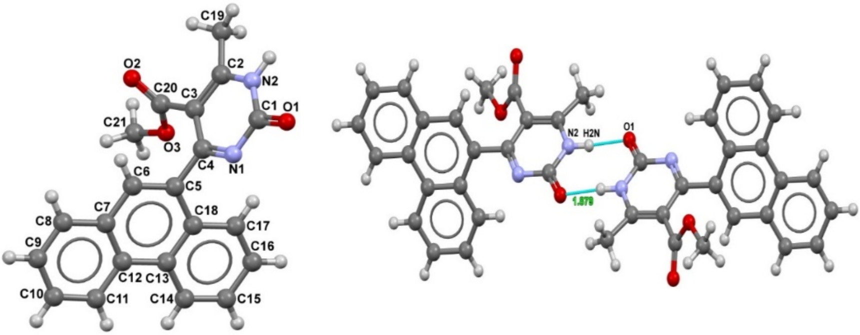


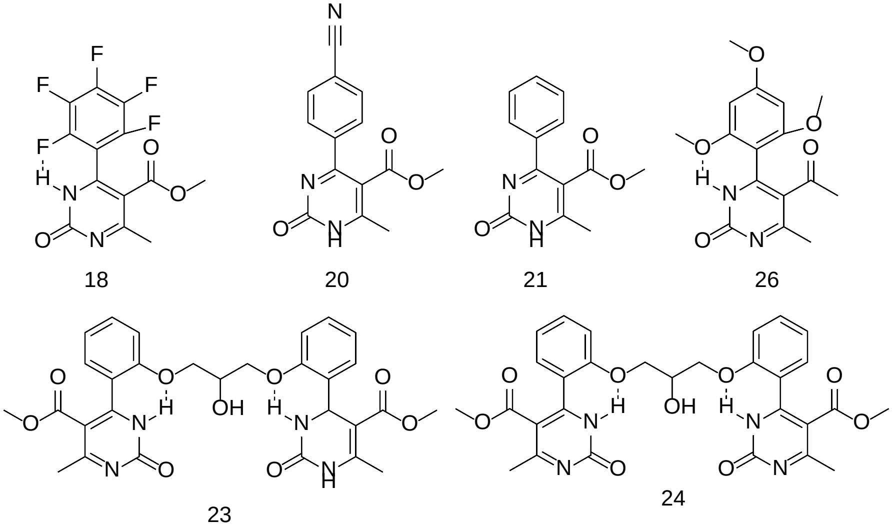
Figure 3. X-ray structure of compound 25 and the dimer formed by a double hydrogen bond

about the stability of one or another tautomer of the oxidation products of dihydropyrimidines and predict the tautomeric form in which the oxidation product will exist, without having data from X-ray structural analysis or 2D NMR spectra. Thus, if a heteroatom is present in the benzene ring, which is capable of participating in the formation of an intramolecular hydrogen bond precisely with the N1H amino group of the dihydropyrimidine ring, then the oxidized product will be in the form of tautomer II. Otherwise, tautomeric form I will exist, which was observed in the case of compounds 22 and 25. Moreover, both tautomer I and tautomer II will exist in crystalline form in the form of a dimer due to intermolecular hydrogen bonds. Moreover, tautomer II will also be characterized by a bifurcation hydrogen bond with bifurcation donors (oxygen of the carbonyl group of the dihydropyrimidine ring and a heteroatom in the ortho position of the benzene ring, capable of forming an intramolecular hydrogen bond with the N1H amino group of the dihydropyrimidine ring), additionally stabilizing the crystalline packing of the compound under study.

Taking into account all of the above, despite the fact that it was not possible to obtain single crystals of oxidized dihydropyrimidines 18, 20, 21, 23, 24 and 26, it is now possible to determine in which tautomeric form the mentioned products of regioselective oxidation will exist. Thus, due to the presence of heteroatoms in the benzene ring capable of participating in the formation of an intramolecular hydrogen bond with the N1H amino group of the dihydropyrimidine ring, compounds 18, 23, 24 and 26 will exist in the form of tautomer II, while due to their absence in compounds 20 and 21, the mentioned oxidized dihydropyrimidines will exist in the form of tautomer I. Moreover, both tautomeric forms will always exist in the form of dimers due to intermolecular hydrogen bonds. In addition to the above, compounds 18, 23, 24 and 26 will be characterized by bifurcation hydrogen bonding with bifurcation donors, namely:

–For compound 18 – a fluorine atom in the ortho position relative to the dihydropyrimidine ring and oxygen of the carbonyl group of the dihydropyrimidine ring

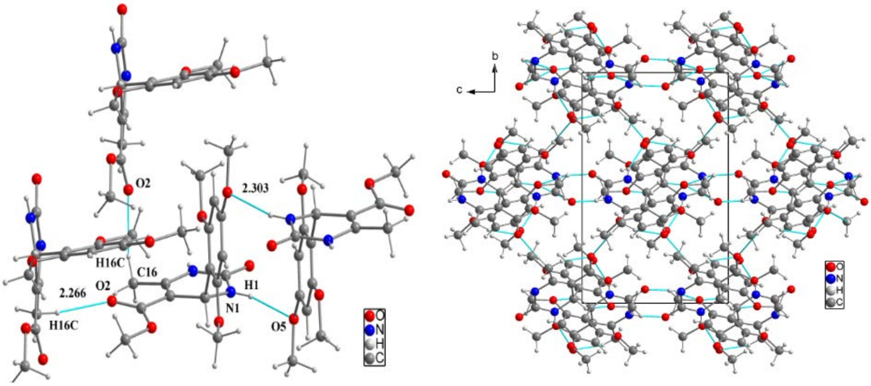
–For compounds 23, 24 and 26 – the oxygen atom is in the ortho position relative to the dihydropyrimidine ring and the oxygen of the carbonyl group of the dihydropyrimidine ring (Scheme 12).



Scheme 12. Proposed tautomeric form of oxidation products

1.1.2. Investigation of crystal packing and determination of the conformation of the dihydropyrimidine ring. Dihydropyrimidines 2, 12, 16, 25 and 9 crystallize in a monoclinic lattice (P21/c), dihydropyrimidine 3 – in a tetragonal lattice (P4/n), dihydropyrimidine 7 – in a monoclinic lattice (C2/c), dihydropyrimidines 8, 19 and 22 – in a triclinic lattice (P-1), dihydropyrimidine 17 – in an orthorhombic lattice (Pna21). The crystal packing of these compounds is mainly stabilized by a network of inter- and intramolecular hydrogen bonds (in the case of all compounds) and stacking interactions (compounds 2, 12, 19 and 22) (Figs. 4–8). Hirshfeld surface analysis showed that the studied compounds exhibit peaks at short distances due to hydrogen bonds, the contribution of which was calculated.

X-ray structural studies have shown (by calculating the “folding parameters”) that the studied dihydropyrimidines 2 and 8 adopt a boat conformation, dihydropyrimidine 3 is a half-boat, dihydropyrimidine 7 is a flattened boat, dihydropyrimidines 9 and 17 are twist-boats, dihydropyrimidine 12 is a flattened boat, and dihydropyrimidine 16 is a half-chair. In the case of molecules 19, 22, and 25, the pyrimidine ring is practically flat.



a **b**

Figure 4. (a) Depiction of hydrogen bonds around an organic molecule, (b) Projection of compound 2 along the **a**-axis.

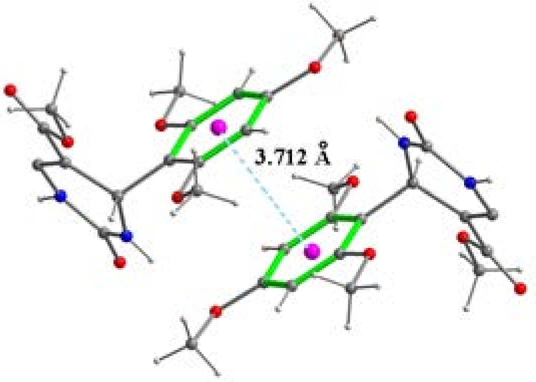
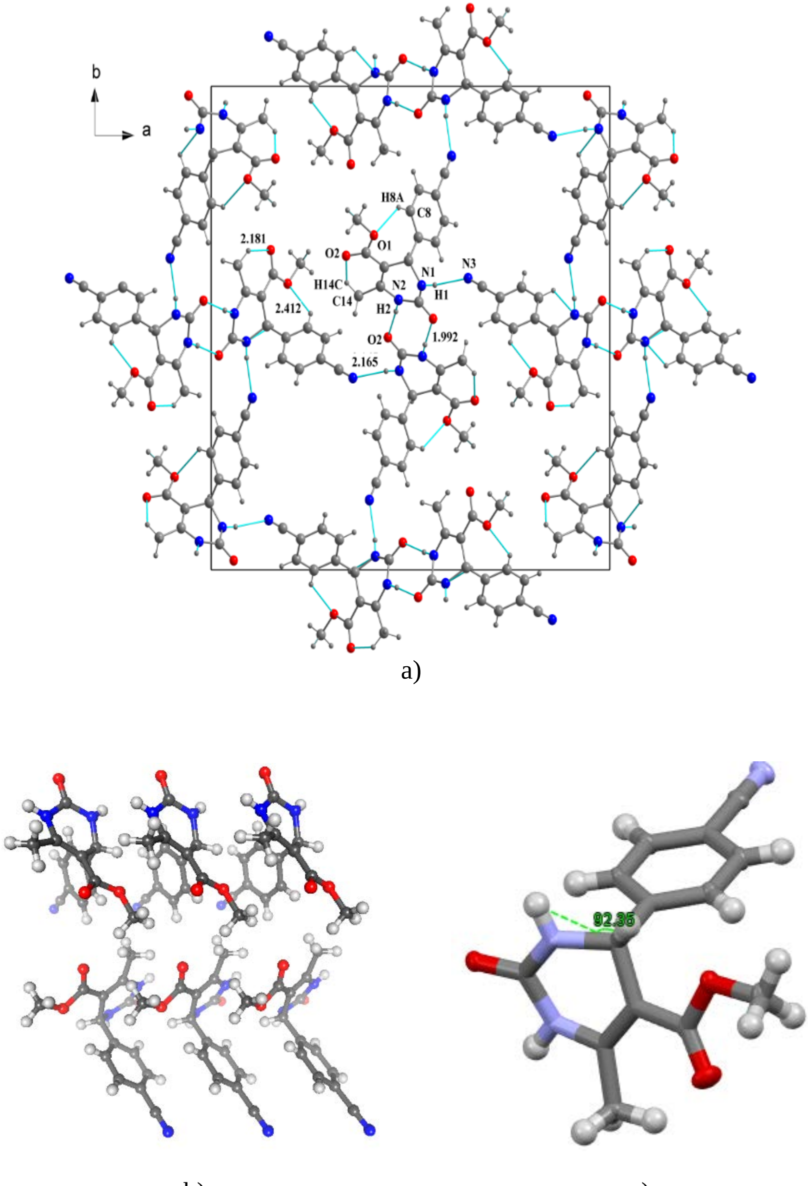


Figure 5. Intermolecular stacking interactions between adjacent aromatic rings in a compound 2

1.2. Synthesis and investigations of nanolayers and ensembles based on them

1.2.1. Synthesis and characterization of graphene oxide nanolayers received on the basis of graphite. The synthesis of graphene oxide nanolayers was carried out by modifying the Hammer method known in the literature. The modification of the method consisted in increasing the amount of oxidizers. The resulting nanolayers were studied by powder X-ray structural analysis (Fig. 9).

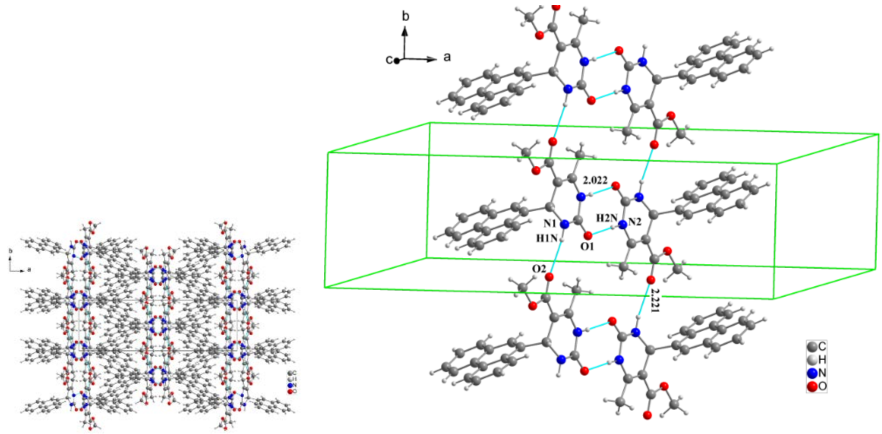


a)

b)

c)

Figure 6. Projection of the structure along the **c**-axis (a), crystallographic autostereogram, horizontal translations along the short **c**-axis (b), dihedral angle (c)



a)　　　　　　　　　　　　　　　　b)

Figure 7. Crystal packing of compound 7 (a), 1D view parallel to c-axis (b) projection along the b-axis. N-H…O hydrogen bonds are represented by blue lines.

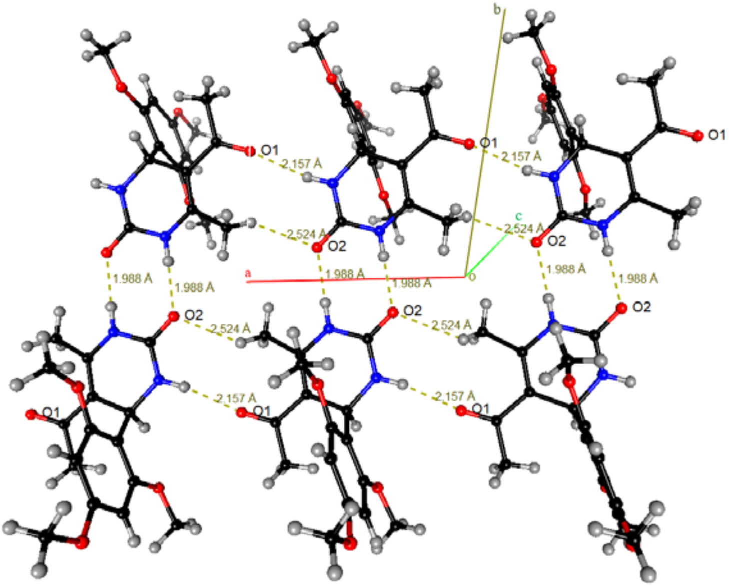


Figure 8. Autostereogram along the ab plane showing molecules linked by C-H···O and N-H···O hydrogen bonds (dashed lines)

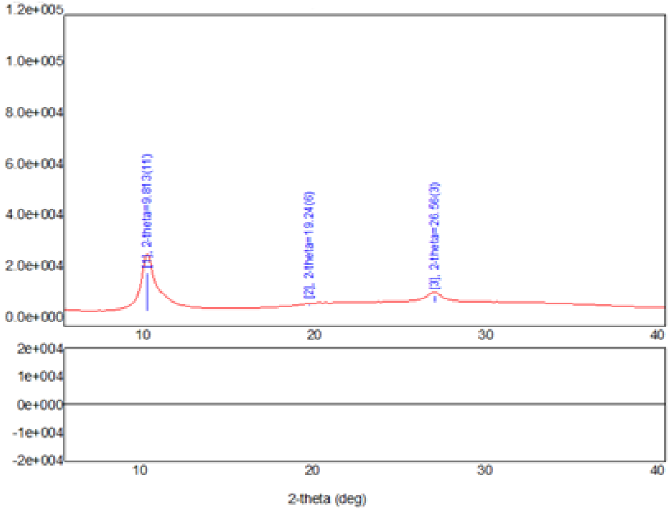


Figure 9. Graphene oxide spectrum

As it can be seen from Fig. 9, the peaks observed at 2ϴ=9.813 and 19.24 are attributed to graphene oxide, and the other peak at 2ϴ=26.56 is attributed to the admixture of unoxidized graphite. In addition, the nanolayers were also studied using the SEM method and elemental analysis (Figs. 10 and 11). As it can be seen from the IR spectrum (Fig. 12), the signals at 3200.29 and 3356.99 sm^{-1} correspond to the phenol and carboxyl hydroxyl groups, respectively. The

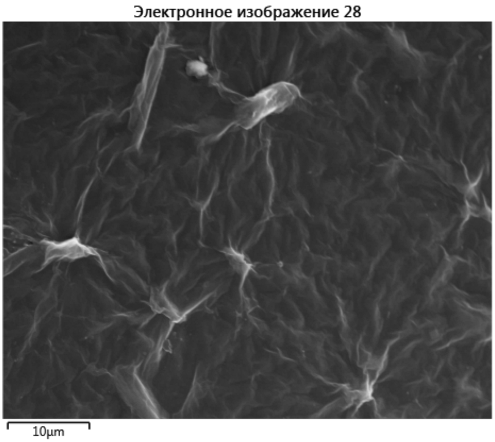


Figure 10. SEM image of graphene oxide

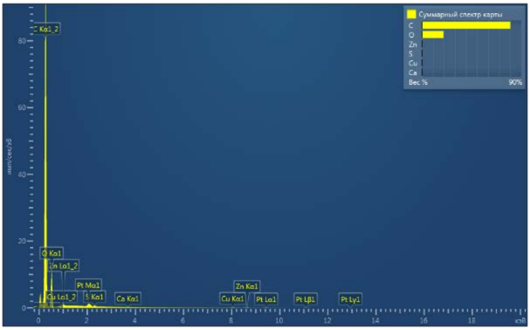


Figure 11. Elemental analysis of graphene oxide

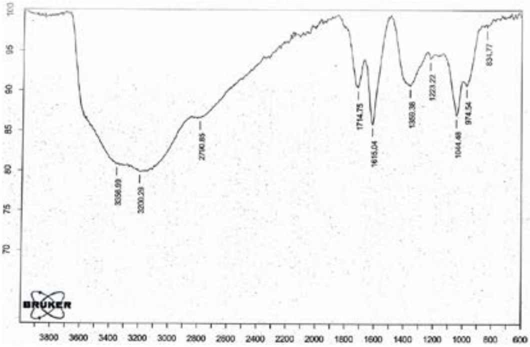


Figure 12. IR spectrum of graphene oxide

frequencies corresponding to epoxy groups (C-O-C) are observed at 1223.22 sm^{-1}. Carbonyl and carboxyl groups are observed at 1714.75 and 1615.04 sm^{-1} respectively. The vibrations observed at 2790.85 sm^{-1} correspond to the stretching vibrations of aromatic C-H groups. The deformation vibrations of sp^2-hybrid CH groups are observed at 1359.38 sm^{-1}.

1.2.2. Synthesis and investigation of ensembles. The obtained graphene oxide nanolayers were sonified in ethanol and then solutions of dihydropyrimidines 2, 3, 5, 8, 11, 14, 15, 16, 17, 21, 22, 23 and 24 were added to them and sonified again. The obtained solutions were evaporated at room temperature and a precipitate was obtained, which was studied using IR spectroscopy.

According to the literature data, the formation of an ensemble can be judged if the spectrum contains minimal (0.1 sm^{-1}) shifts or degeneracies of certain signals that had low intensity in the original spectrum. Moreover, the greater the shift or degeneracy, the stronger the non-covalent interaction involving this group. As it can be seen from Figs. 13 and 14, simple comparison of the spectra of individual dihydropyrimidine 16 and the 16@GO ensemble reveals a shift of the signals in the spectra due to the non-covalent interaction between the dihydropyrimidine molecules and graphene oxide. Thus,

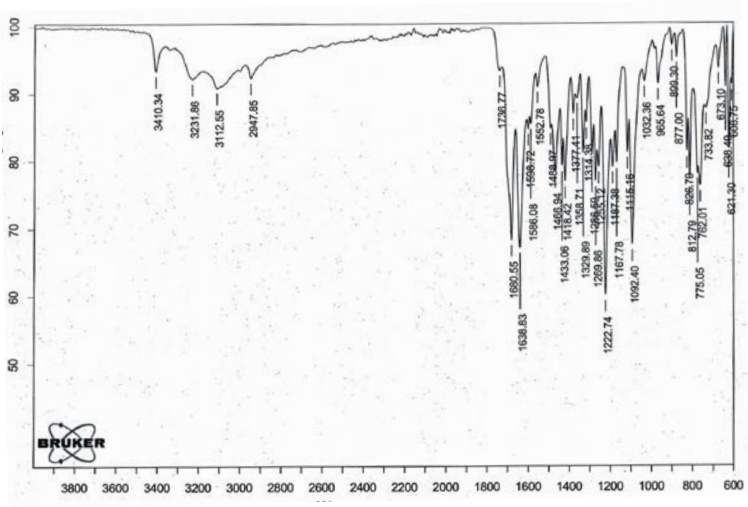


Figure 13. IR spectrum of dihydropyrimidine 16

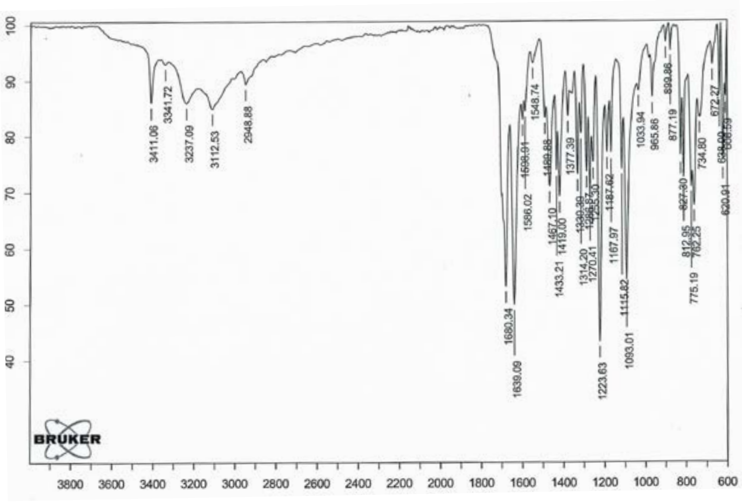


Figure 14. IR spectrum of the ensemble of 16@GO

the signal observed at 3410.34 sm^{-1} in the spectrum of individual dihydropyrimidine 16 is observed at 3411.06 sm^{-1} in the spectrum of the ensemble. The shift is 0.6 sm^{-1}. The signals in the spectrum of individual dihydropyrimidine 16, observed at 3231.86 and 2947.85 sm^{-1}, in the spectrum of the ensemble are observed at 3237.09 and 2948.88 sm^{-1}, respectively. The shift is 5.23 and 1.03 sm^{-1}, respectively. Comparison of the remaining signals also shows a certain shift or degeneration of the signals. Based on the fact that the above regions (and, accordingly, the shifts in these regions) correspond to hydroxyl and amine groups, it can be assumed that the greatest contribution to the non-covalent interaction between the dihydropyrimidine molecule and graphene oxide is made by hydrogen bonds.

1.3. Biological investigations

The following activities of dihydropyrimidines and ensembles based on them were investigated: antiparasitic, anticancer, cytotoxic, antibacterial, and antifungal. Modification of the studied compounds with graphene oxide nanolayers in most cases led to an increase in the biological activity of the original dihydropyrimidines (Tables 4 and 5).

Table 4. Antiparasitic activity of dihydropyrimidine 16 and its ensemble

T. brucei		*Leishmania*	
Investigation sample	IC$_{50}$ (μM)	Standard	IC50 (μM)
16	25.1	2.3	>100
16@GO	20		>100

Table 5. Activity of dihydropyrimidine 16 and its ensemble on HT-29 and MRC-5 cell lines

HT-29			MRC-5	
Investigation sample	IC$_{50}$ (μM)	Standard	Standard	IC$_{50}$ (μM)
16	75	2	21	52
16@GO	60			45

1.4. In silico analysis

The required quantum-chemical parameters of the studied compounds 12, 16, 17, 5 and 22 were determined using the Gaussian package. The energies of the MEP, HOMO, LUMO, ΔE and the electrostatic potential were also studied.

Next, molecular docking calculations were performed to investigate the possible binding of dihydropyrimidine 12 with various proteins dihydropyrimidines 16 and 17 with Candida albicans thymidylate kinase, and dihydropyrimidines 5 and 22 with chitin deacetylase. The data obtained allow us to conclude that the interaction of the studied molecules with the selected proteins occurs better in comparison with the reference substances.

CONCLUSIONS

1. An effective method for the synthesis of dihydropyrimidines by the Biginelli reaction in the presence of copper triflate and cerium chloride under microwave conditions has been developed. The effect of copper triflate on the process of obtaining dihydropyrimidines based on salicylic aldehyde derivatives has been studied and the formation of 2-hydroxyaryl derivatives of dihydropyrimidines has been proven [1, p. 128581; 2, p. 130678; 4, p. 109; 6, p. 52; 7, p. 6312; 8, p. 31; 11, p. 154]
2. New derivatives of dihydropyrimidines were obtained by regioselective oxidation of Biginelli reaction products in the presence of cerium ammonium nitrate [2, p. 130678; 6, p. 52; 7, p. 6312; 9, p. 104; 10, p. 151; 11, p. 154].
3. The presence of various non-covalent interactions in single crystals of dihydropyrimidines was determined by single X-ray diffraction method, their influence on the crystal packing, the conformation of the dihydropyrimidine ring and the tautomeric process of oxidation products was investigated [1, p. 128581; 2, p. 130678; 3, p. 133571; 4, p. 109; 6, p. 52; 7, p. 6312].
4. The intermolecular interactions of the synthesized dihydropyrimidines were also studied by the Hirshfeld surface analysis method and their “fingerprints” were shown [1, p. 128581; 2, p. 130678; 3,

p. 133571; 4, p. 109; 6, p. 52; 7, p. 6312].

5. Various assemblies were obtained based on synthesized dihydropyrimidine derivatives and graphene oxide nanolayers, which was synthesized by the modified Hammer method [5, p. 142; 12, p. 42; 13, p. 37; 14, p. 88].
6. The biological activity of the obtained dihydropyrimidines and ensembles was investigated using experimental methods and by comparing the results obtained with the activities of known drugs, the most biologically active dihydropyrimidines and ensembles were identified. It was found that graphene oxide in some cases improved the activity of dihydropyrimidines [1, p. 128581; 2, p. 130678; 4, p. 109; 5, p. 142].
7. Computational analyses were also performed, which allowed to calculate the quantum-chemical parameters of the investigate molecules. Molecular docking was performed to explain the biological activity, which allowed to determine the target proteins inhibited by the investigated dihydropyrimidines. The amino acid fragments involved in the interaction with the active molecules were also determined. [3, p. 133571; 4, p. 109; p, c. 52].

The following scientific papers have been published based on the dissertation materials:

1. Huseynzada, A.E. Synthesis, crystal structure and antibacterial properties of 6-methyl-2-oxo-4-(quinolin-2-yl)-1,2,3,4-tetrahydropyrimidine-5 carboxylate / A.E.Huseynzada, C.Jelsch, H.N.Akhundzada [et al.] // Journal of Molecular Structure, – 2020. v. 1219, – p. 128581-1-21.
2. Huseynzada, A.E. Synthesis, crystal structure and antibacterial studies of 2,4,6-trimetoxybenzaldehyde based dihydropyrimidine derivatives / A.E.Huseynzada, C.Jelsch, H.N.Akhundzada [et al.] // Journal of Molecular Structure, – 2021. v. 1241, – p. 130678-1-24.
3. Huseynzada, A. Synthesis, crystal structure, Hirshfeld surface, computational and antibacterial studies of a 9-phenanthrenecarboxaldehyde-based thiodihydropyrimidine derivative / A.Huseynzada, M.Mori, F.Meneghetti [et al.] // Journal of Molecular Structure, –

2022. v. 1267, – p. 133571-1-7.

4. Huseynzada, A.E. Crystal structure, Hirshfeld surface analysis, computational and antifungal studies of dihydropyrimidines on the basis of salicylaldehyde derivatives / A.E.Huseynzada, C.Jelsch, H.V.Akhundzada [et al.] // Journal of the Iranian Chemical Society, – 2023. v. 20, № 1, – p. 109-123.
5. Huseynzada, A., Hasanova, U., Gakhramanova, Z. Graphene oxide-modified dihydropyrimidines // Azerbaijan Chemical Journal, – 2023. v. 3, – p. 142-151.
6. Huseynzada, A. Crystal Structure, Hirshfeld Surface Analysis, In-Silico and Antimycotic Investigations of Methyl 6-methyl-4-(4-nitrophenyl)-2-oxo-1,2-dihydropyrimidine-5-carboxylate / A.Huseynzada, M.Mori, F.Meneghetti [et al.] // Crystals, – 2022. v. 13, № 1, – p. 52-72.
7. Huseynzada, A.E. Synthesis, crystal structure and antibacterial studies of dihydropyrimidines and their regioselectively oxidized products / A.E.Huseynzada, C.Jelch, H.V.N.Akhundzada [et al.] // RSC Advances, – 2021. v. 11, № 11, – p. 6312-6329.
8. Huseynzada, A.E. Synthesis of new hydroxy substituted dihydropyrimidines and investigation of their antifungal activity against *Candida albicans* // Journal of Baku Engineering University, – 2019. v. 3, № 1, – p. 31-37.
9. Гусейнзаде, А.Э. Исследование реакции окисления дигидропиримидина в присутствии церий аммоний нитрата // Gənc tədqiqatçı, – 2019. c. V, №2, –s. 104-110.
10. Гасанова, У.А., Гусейнзаде, А.Э., Агаев, М.М., Гаджиева, С.Ф., Магеррамов, А.М. Исследование реакции окисления дигидропиримидина, полученного на основе диальдегида в присутствии церий аммоний нитрата // II Международная Научная Конференция Молодых Исследователей, посвященная 95-летию Общенационального лидера Азербайджана Гейдара Алиева,– Баку, Бакинский Инженерный Университет, Азербайджан: – 27 – 28 апреля, – 2018, – с. 151-153.
11. Гасанова, У.А., Гусейнзаде, А.Э., Гасанова, И.Р., Гулиева, Н.А., Эйвазова, Г.М., Магеррамов, А.М. Синтез и исследова-

ние дигидропиримидинов, полученных на основе пентафторобензальдегида по реакции Биджинелли // II Международная Научная Конференция Молодых Исследователей, посвященная 95-летию Общенационального лидера Азербайджана Гейдара Алиева, – Баку, Бакинский Инженерный Университет, Азербайджан: – 27 – 28 апреля, – 2018, – с. 154-156.

12. Huseynzada, A.E., Israyılova, A.A., Hasanova, I.R, Hasanova, U.A. Graphene oxide-dihydropyrimidine based supramolecular ensembles as an effective antibacterial agent // 10th Rostocker International Conference: “Thermophysical Properties for Technical Thermodynamics”, – Rostock, Germany: – 09 – 10 September, – 2021, – p. 42.
13. Maharramov, A.M., Hasanova, U.A., Ramazanov, M.A., Karacelik, A., Hasanova, İ.R., Huseynzada, A.E., Aliyev, A.R., Imamgulıyeva, L.A., Imanzade, G.A. Synthesis of supramolecular ensembles on the basis of nano layers of graphene oxide // 6th Rostocker International Conference: “Thermophysical Properties for Technical Thermodynamics”, – Rostock, Germany: – 17 – 18 iyul, – 2017, – p. 37.
14. Maharramov, A.M., Huseynzada, A.E., Aghayev, M.M., Hajiyeva, S.F., Hasanova, I.R., Guliyeva, N.A., Akhundova, M.A., Aliyeva, G.A, Aghasiyev, J.F. Synthesis of graphene oxide modified supramolecular ensembles and their application // 7th Rostocker International Conference: “Thermophysical Properties for Technical Thermodynamics”, – Rostock, Germany: – 26 – 27 July, – 2018, – p. 88.

The defence will be held on 25 june 2025 year at 11⁰⁰ at the meeting of the Dissertation Council ED 2.16 of Supreme Attestation Commission under the President of the Republic of Azerbaijan operating at Baku State University.

Address: AZ 1148, Baku, Z. Khalilov, 33

Dissertation is accessible at the Baku State University Library.

Electronic versions of dissertation and its abstract are available on the official website of the Baku State University (www.bsu.edu.az).

Abstract was sent to the required addresses on 23 may 2025 year.

Signed for print: 16.05.2025
Paper format: 60×90 1/16
Volume: 39 416
Number of hard copies: 20