Current research trends of 1,2,4-triazole derivatives biological activity (literature review)

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A – research concept and design; B – collection and/or assembly of data; C – data analysis and interpretation; D – writing the article; E – critical revision of the article; F – final approval of the article

The relevance of searching for new active compounds among 1,2,4-triazole derivatives is determined by their potential effectiveness in treating various diseases such as cancer, inflammation, microbial infections, and antioxidant disorders. Studies show that these compounds can inhibit the proliferation of cancer cells, exhibit anti-inflammatory properties, demonstrate activity against pathogenic microorganisms, and neutralize free radicals, which is important for preventing oxidative stress. Therefore, the study of 1,2,4-triazole derivatives may lead to the development of new effective drugs, which is extremely relevant in modern medicine.

The aim of the work is to summarize recent scientific advances in the study of 1,2,4-triazole derivatives, particularly their antitumor, antimicrobial, anti-inflammatory, anticonvulsant, and antioxidant activity, to substantiate their potential as multifunctional therapeutic agents in modern medicine.

Results. The literature review confirmed that 1,2,4-triazole derivatives exhibit significant biological activity across various therapeutic areas. Studies revealed high antitumor efficacy of hybrid compounds, particularly the derivative 5-((4-(6-fluorobenzo[d]isoxazol-3-yl)piperidin-1-yl) methyl)-4-(4-nitrophenyl)-4*H*-1,2,4-triazole-3-thiol, which demonstrated notable activity against breast cancer cells (MCF-7), as confirmed by DFT and molecular docking methods. In antimicrobial therapy, derivatives combined with norfloxacin showed higher efficacy compared to standard antibiotics against both Gram-positive and Gram-negative bacteria while maintaining good biocompatibility. Research on anticonvulsant properties found that 4-amino-4*H*-1,2,4-triazole derivatives effectively interact with the GABA-A receptor, outperforming the standard drug phenytoin in *in vivo* models. In anti-inflammatory studies, compounds containing a 1,3,4-thiadiazine fragment achieved 91 % inhibition of edema, surpassing ibuprofen (82 %), and reduced key inflammatory biomarkers. The antioxidant properties of brominated [1,2,4]triazolo[1,5-a]pyridine derivatives were particularly pronounced, with maximum activity observed at a concentration of 150 μg/mL. These results highlight the broad therapeutic potential of 1,2,4-triazole derivatives, making them promising candidates for the development of novel drugs to combat oncological, infectious, inflammatory, and neurodegenerative diseases, as well as for oxidative stress prevention.

Conclusions. 1,2,4-Triazole derivatives exhibit a wide range of biological activity, including antifungal, antimicrobial, anticancer, antibacterial, anticonvulsant, anti-inflammatory, and antioxidant properties. This indicates their potential as versatile agents for the treatment of various diseases.

Keywords: derivatives 1,2,4-triazole, biological activity.

Current issues in pharmacy and medicine: science and practice. 2025;18(2):197-205

Сучасні напрями досліджень біологічної активності похідних 1,2,4-тріазолу (огляд літератури)

І. М. Білай, В. І. Дарій, А. В. Хільковець, А. І. Білай

Актуальність пошуку нових активних сполук у похідних 1,2,4-тріазолів зумовлена їхньою потенційною ефективністю під час лікування пацієнтів із різними станами: онкологічними процесами, запаленням, мікробними інфекціями та порушеннями антиоксидантної системи. Згідно з результатами досліджень, ці сполуки можуть інгібувати проліферацію ракових клітин, мають протизапальні властивості, активність проти патогенних мікроорганізмів і можуть нейтралізувати вільні радикали, що важливо для профілактики оксидативного стресу. Отже, вивчення похідних 1,2,4-тріазолів може сприяти розробленню нових ефективних лікарських засобів, що є надзвичайно актуальним у сучасній медицині.

Мета роботи – узагальнення останніх наукових досягнень у дослідженні похідних 1,2,4-тріазолів, зокрема щодо протипухлинної, антимікробної, протизапальної, протисудомної та антиоксидантної активності, для обґрунтування їхнього потенціалу як багатофункціональних терапевтичних агентів у сучасній медицині.

Результати. Похідні 1,2,4-тріазолів характеризуються значною біологічною активністю різних терапевтичних напрямів. У результаті досліджень виявлено високу протипухлинну ефективність гібридних сполук, зокрема похідної 5-((4-(6-фторбензо[d]ісоксазол-3-іл)

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піперидин-1-іл)метил)-4-(4-нітрофеніл)-4*H*-1,2,4-тріазол-3-тіол, що чинила значну активність проти клітин раку молочної залози (MCF-7). Це підтверджено методами DFT і молекулярного докінгу. Щодо антимікробної активності встановлено, що похідні, поєднані з норфлоксацином, мали вищу ефективність порівняно зі стандартними антибіотиками проти грампозитивних, грамнегативних бактерій і зберігали хорошу біосумісність. Під час дослідження протисудомних властивостей виявили, що похідні 4-аміно-4*H*-1,2,4-тріазолу ефективно взаємодіють із рецептором GABA-A, сприяли кращим результатам лікування порівняно з фенітоїном у моделях *in vivo*. Як засоби для протизапальної терапії сполуки з фрагментом 1,3,4-тіадіазину сприяли інгібуванню набряку (91 %), перевершивши ефективність ібупрофену (82 %), а також знизили рівень ключових запальних біомаркерів. Антиоксидантні властивості бромованих похідних [1,2,4]тріазоло[1,5-a]піридину виражені особливо, максимальна активність зафіксована при концентрації 150 мкг/мл. Ці результати свідчать про широкий терапевтичний потенціал похідних 1,2,4-тріазолів, що робить їх перспективними кандидатами для розробки нових лікарських засобів для лікування пацієнтів з онкологічними, інфекційними, запальними та нейродегенеративними захворюваннями, а також для профілактики оксидативного стресу.

Висновки. Похідні 1,2,4-тріазолів характеризуються широким спектром біологічної активності: протигрибковою, протимікробною, протираковою, антибактеріальною, протисудомною, протизапальною та антиоксидантною. Це свідчить про їхній потенціал як універсальних засобів для лікування різних захворювань.

Ключові слова: похідні 1,2,4-тріазолу, біологічна активність.

Актуальні питання фармацевтичної і медичної науки та практики. 2025. Т. 18, № 2(48). С. 197-205

Derivatives of 1,2,4-triazoles attract considerable attention in modern chemistry due to their diverse biological properties and potential for medical use [1,2]. These compounds have proven to be effective in treating various diseases, such as cancer, infectious diseases, inflammatory processes, and diseases of the cardiovascular system. Current research highlights their antibacterial, antiviral, anti-inflammatory, and cytostatic activity, making them promising candidates for the development of new drugs [3,4]. In addition, most representatives of this class are low-toxic or practically non-toxic substances, which is also their significant advantage [5,6]. A successful example of this is Thiotriazoline, which is known for its antioxidant, hepatoprotective, and cardioprotective properties. It is widely used in medicine for the treatment of liver diseases, cardiovascular disorders, and conditions associated with oxidative stress.

Due to the variety of synthetic approaches and the ability to modify the structure of 1,2,4-triazoles [7,8], an objective assessment of their biological activity is crucial for the development of effective drugs. The literature review will not only analyze the results already achieved, but also point out knowledge gaps that require further study.

The literature review on current trends in the study of the biological activity of 1,2,4-triazole derivatives is important for systematizing existing knowledge and identifying directions for further research. Currently, there are numerous publications describing new synthetic methods, mechanisms of action, and clinical trials of triazole derivatives, but it is necessary to summarize these data and identify key trends in this area [9,10].

Therefore, the study of current trends in this area is an important contribution to pharmaceutical science, which will contribute to the development of new therapeutic strategies.

Aim

The aim of the work is to summarize recent scientific advances in the study of 1,2,4-triazole derivatives, particularly their antitumor, antimicrobial, anti-inflammatory, anticonvulsant, and antioxidant activity, to substantiate their potential as multifunctional therapeutic agents in modern medicine. The review aims to identify major research trends, identify knowledge gaps, and formulate recommendations for further experimental studies to develop new therapeutics based on these compounds.

Materials and methods

The study employed the following methods: analytical, information search, descriptive, and generalization. The sources of materials included data from domestic information and scientific databases, as well as scientometric platforms such as Scopus, Web of Science, and PubMed over the past five years. The literature search was conducted using the following selection criteria: peer-reviewed publications investigating the biological activity of 1,2,4-triazole derivatives. Articles were screened based on titles, abstracts, and keywords, with additional filters applied for publication year, full-text availability, and study type.

Results

Today, the search for antitumor agents is due to the growing prevalence of cancer worldwide [11,12]. Traditional treatments, such as chemotherapy and radiotherapy, are often accompanied by serious side effects and tumor resistance to therapy. Therefore, there is an urgent need to develop new drugs that can provide more effective treatment with minimal side effects.

A joint group of Chinese and Indian scientists [13] synthesized and investigated a series of six new hybrids of 1,2,4-triazole and the aromatic fragment of benzisoxazole. The compounds were subsequently studied for antitumor activity, namely against MCF-7 cells (breast cancer cells). To evaluate the antitumor activity of derivatives, the Alamar Blue assay method was used on a well-characterized MCF-7 cell line, which is widely used in scientific research. The compounds were tested in various concentrations up to 100 microns for 72 hours. Of the six compounds, 5-((4-(6-fluorobenzo[d] isoxazol-3-yl)piperidin-1-yl)methyl)-4-(4-nitrophenyl)-4*H*-1,2,4-triazole-3-thiol *(Fig. 1)* demonstrated a high activity against the studied cells. To confirm and explain the obtained results, the Density functional theory method and molecular

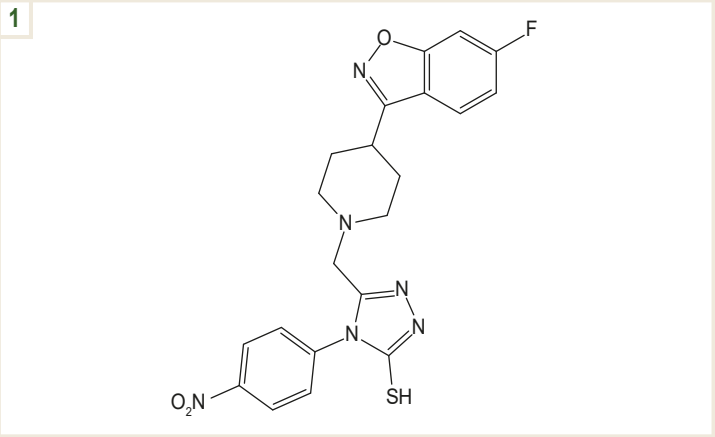

Fig. 1. 5-((4-(6-Fluorobenzo[d]isoxazol-3-yl)piperidin-1-yl)methyl)-4-(4- nitrophenyl)-4*H*-1,2,4-triazole-3-thiol.

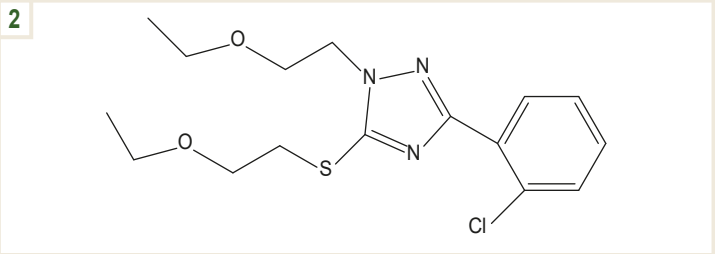

Fig. 2. Derivatives containing 5-(2-chlorophenyl)-2,4-dihydro-1,2,4-triazole-3-thione.

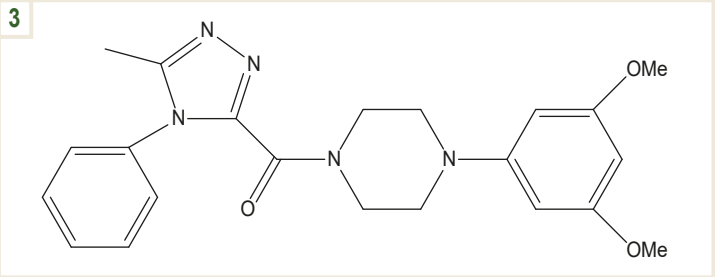

Fig. 3. (4-(3,5-Dimethoxyphenyl)piperazin-1-yl)(5-methyl-4-phenyl-4H-1,2,4-triazol-3-yl)methanone.

docking were also used. They showed that this molecule is characterized by a small energy gap value, which indicates its high reactivity.

For the same purpose, M. R. Aouad, H. M. Al-Mohammad et al. invented a convenient and efficient regioselective synthesis of a series of S- and S,N-bis-acyclonucleoside derivatives containing 5-(2-chlorphenyl)-2,4-dihydro-1,2,4-triazole-3-thion, as well as direct synthesis of triazolothiazines *(Fig. 2)* [14]. Scientists analyzed the obtained compounds for cytotoxicity against three types of human liver cancer cells (Hep G2, MCF-7, HCT116). To obtain detailed data on the mechanism of action, EGFR analysis and tubulin inhibition analysis were performed for the most active compounds. According to the results, it was found that some of the obtained substances exhibit a significant anti-cancer effect.

A group of scientists [15] synthesized several 5-methyl-4-aryl-3-(4-arylpiperazine-1-carbonyl)-4*H*-1,2,4-triazoles and studied their antiproliferative and inhibitory effects on tubulin polymerization. According to the results of the study, it became known that some compounds of the series showed moderate activity *in vitro* against three cancer cell lines SGC-7901, A549 and HeLa. The compound (4-(3,5-dimethoxyphenyl) piperazine-1-yl)(5-methyl-4-phenyl-4*H*-1,2,4-triazole-3-yl) methanone *(Fig. 3)* found the highest efficacy against three cancer cell lines).

Around the world, many new strains of microorganisms have recently been discovered that show resistance to antimicrobial agents, which poses a serious threat to health. Improving existing and creating new effective synthetic drugs against microbes and fungi is one of the priorities of the modern pharmaceutical industry. For this purpose, derivatives of 1,2,4-triazoles are actively studied [16,17].

Scientists have obtained a series of new "1,2,4-triazole-norfloxacin" hybrids *(Fig. 4)*. The resulting compounds showed higher antibacterial activity compared to norfloxacin against both Gram-positive and Gram-negative bacteria [18]. It was

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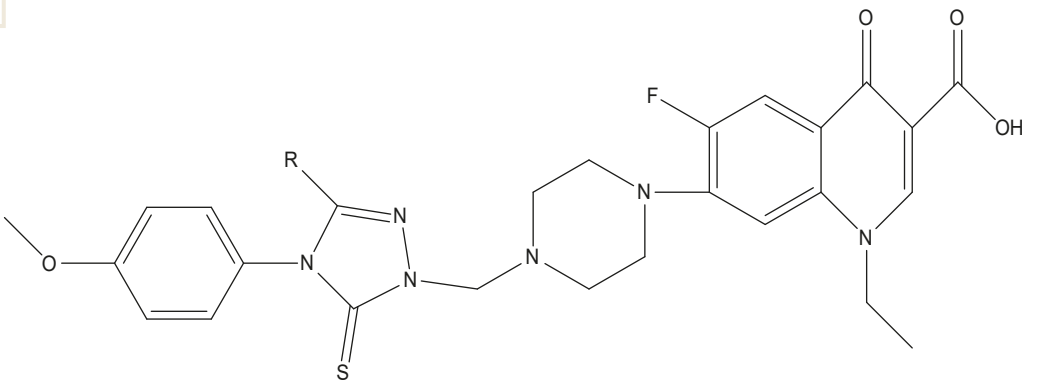

Fig. 4. New "1,2,4-triazole-norfloxacin" hybrids.

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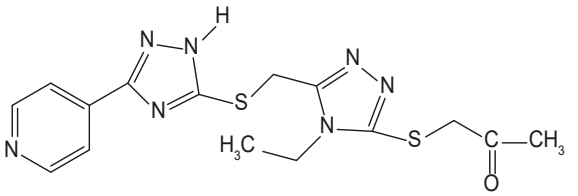

Fig. 5. 1-((4-Ethyl-5-(((3-(pyridin-4-yl)-1H-1,2,4-triazol-5-yl)thio)methyl)-4*H*-1,2,4-triazol-3-yl)thio)propan-2-one.

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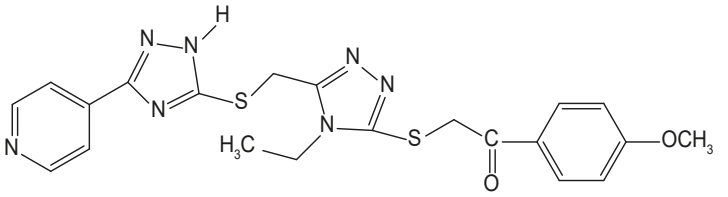

Fig. 6. 1-(4-Methoxyphenyl)-2-((4-ethyl-5-(((3-(pyridin-4-yl)-1*H*-1,2,4-triazol-5-yl)thio)methyl)-4*H*-1,2,4-triazol-3-yl)thio)ethanone.

found that hemolysis is not observed at a concentration of 64 micrograms/ml, which indicates good biocompatibility of the molecules. According to the results of molecular docking, the lowest binding energy varies from 9.4 kcal/mol to 9.7 kcal/mol.

Scientists of Zaporizhzhia State Medical and Pharmaceutical University [19] obtained and investigated several new S-substituted 1,2,4-triazole-3-thiols from 2-aryl-2-oxoethane-1-yl substitute. Further research focused on their antibacterial and antifungal activity. Strains of *Staphylococcus aureus* ATCC 25923, *Escherichia coli* ATCC 25922, *Pseudomonas aeruginosa* ATCC 27853, and *Candida albicans* ATCC 885-653 were used as test cultures. Activity was evaluated by the method of double serial dilutions in a liquid nutrient medium, which was optimal for the growth of the studied cultures, at a concentration of 106 cells/ml. The minimum inhibitory concentration was determined by the absence of visible growth *in vitro* at the lowest concentration of the test sample. The highest activity was demonstrated by compounds 1-((4-ethyl-5-(((3-(pyridin-4-yl)-1*H*-1,2,4-triazol-5-yl) thio)methyl)-4*H*-1,2,4-triazol-3-yl)thio)propan-2-one and 1-(4-methoxyphenyl)-2-((4-ethyl-5-(((3-(pyridine-4-yl)-1*H*-1,2,4-triazole-5-yl)thio)methyl)-4*H*-1,2,4-triazole-3-yl)thio) ethanone *(Fig. 5, 6)*. The results show that these substances are promising for further research.

The search for new synthetic compounds with anticonvulsant activity remains an important direction in modern pharmaceutical science. Among the reasons for this are the high level of resistance to traditional anticonvulsants, significant side effects of existing drugs, and the need for therapies that could be more effective in treating various forms of epilepsy [20,21]. Research of new molecules can not only expand the arsenal of therapeutics, but also understand the mechanisms of convulsive seizures, which can contribute to the creation of targeted and personalized treatment strategies.

A team of Indian scientists [22] obtained new derivatives of 4-amino-4*H*-1,2,4-triazole using various arylaldehydes and ketones *(Fig. 7)*. The resulting compounds were tested for anticonvulsant activity and their neurotoxicity *in vivo*. Two compounds from a number of those obtained showed better results compared to the control agent phenytoin. The direct structure-action relationship was studied, in one case

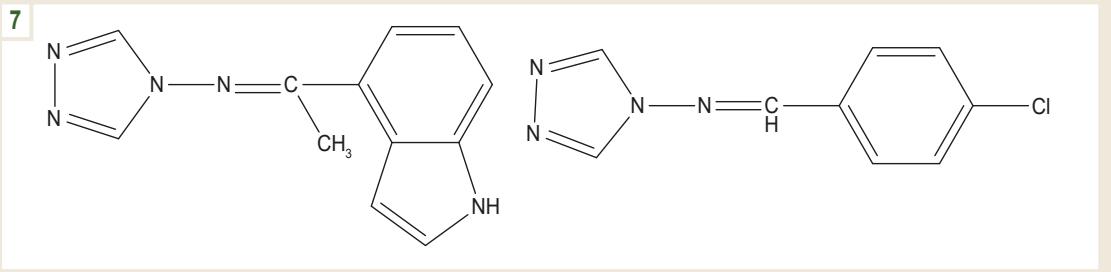

Fig. 7. Derivatives of 4-amino-4*H*-1,2,4-triazole.

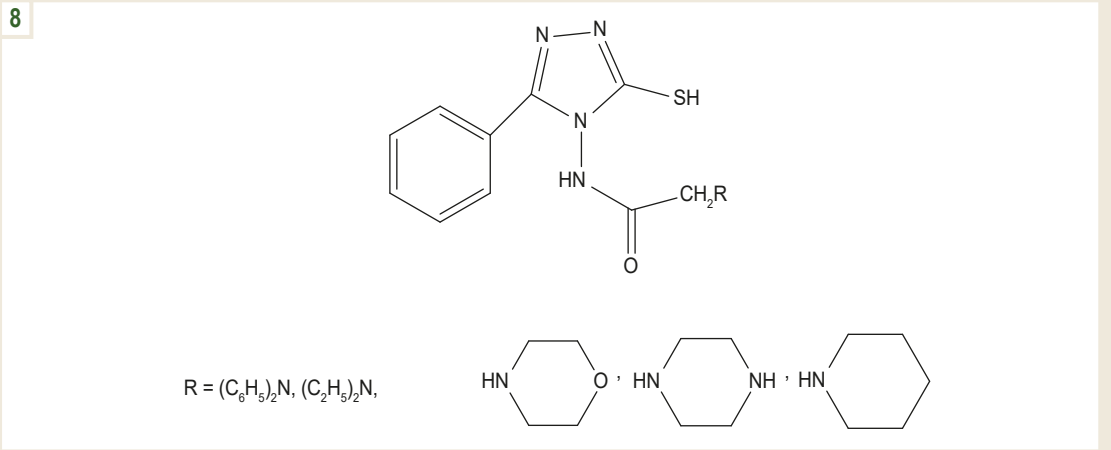

Fig. 8. 5-Aryl-4-(chloroacetylamino)-3-mercapto-1,2,4-triazole.

due to the existing electron – acceptor group of halogens, in the second – heterocyclic aromatic indole. Thus, it was found that the nature of functional groups is crucial for anticonvulsant activity.

Another team of Indian scientists, Rupshee Jain et al. [23], used organic synthesis methods to obtain several derivatives of 5-aryl-4-(chloracetylamino)-3-mercapto-1,2,4-triazole *(Fig. 8)*. For detailed study and analysis, the researchers used methods for predicting pharmacologic activity, the *in silico* molecular docking method, and experimental *in vivo* models: maximum electric shock-induced seizures (MES) and pentylenetetrazole-induced seizures (scPTZ). Phenytoin and carbamazepine were used as standard drugs to assess the anticonvulsant activity of synthesized compounds. Molecular docking was performed to evaluate binding affinities to the GABA receptor and qualitatively substantiate their anticonvulsant activity. Molecular dynamics modeling revealed the structural stability of the GABAA ligand complex in a dissolved medium. Among the synthesized compounds, thiazole and 1,2,4-triazole derivatives showed high results. These compounds may even be considered potential therapeutic candidates in preclinical and clinical trials as effective antiepileptic drugs.

Inflammation is an important process that significantly affects the development of many diseases, in particular autoimmune disorders, cardiovascular diseases and cancer. Studying the mechanisms of inflammation helps to create effective treatment strategies that aim to reduce the inflammatory response [24,25]. Most nonsteroidal anti-inflammatory drugs affect the synthesis of inflammatory mediators, in particular arachidonic acid metabolites, by inhibiting cyclooxygenase activity. However, there is another pathway – lipoxygenase, which involves the sequential interaction of different subtypes of lipoxygenases. As a result, various subtypes of leukotrienes and lipoxins are formed from arachidonate.

Shahid W. et al. actively studied the inhibitory activity of newly synthesized S-alkyl/aralkyl derivatives of 2-(4-ethyl/phenyl-5-(1-phenylcarbamoylpiperidine)-4*H*-1,2,4-triazole-3-yl-thio)esther against lipoxygenase *(Fig. 9)* [26]. In the course of the work, a number of methods were applied, in particular *in vitro*, *in silico*, MTT analysis and flow cytometry, which gave interesting results. For some compounds, strong inhibitory properties were found against the human enzymes 15-sLOX and 5-LOX human (5-hLOX), and they also showed maximum cell viability of lymphocytes and effects on cells in the late apoptosis stage. Based on the obtained data, work was continued on the search for an active anti-inflammatory agent.

Neelakanth M. Jeedi et al. [27] conducted a few interesting studies on the analgesic and anti-inflammatory activity of newly synthesized 1,2,4-triazole derivatives *(Fig. 10)*. The anti-inflammatory properties were tested with carrageenan and formalin-induced rat paw edema, and the twists caused by acetic acid were also investigated. Peripheral and central analgesic effects were evaluated using the hot plate method. Diclofenac and pentazocine were used as comparison tools. The compound (5-(4-nitrophenyl)-1-phenyl-1*H*-1,2,4-tri-

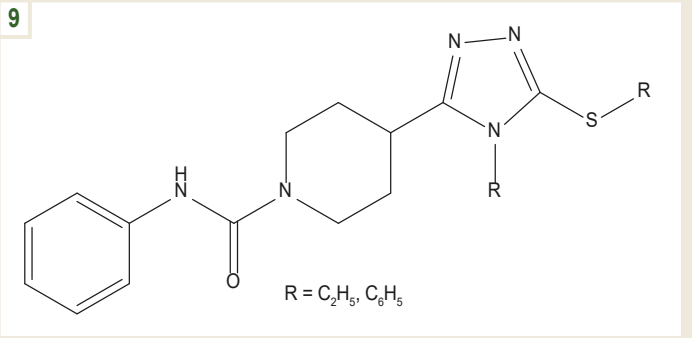

Fig. 9. N-ethyl/phenyl-3,5-disubstituted triazoles.

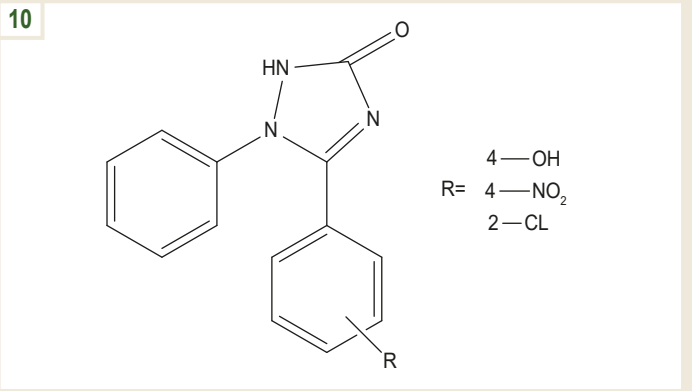

Fig. 10. Derivatives of 1,2,4-triazole.

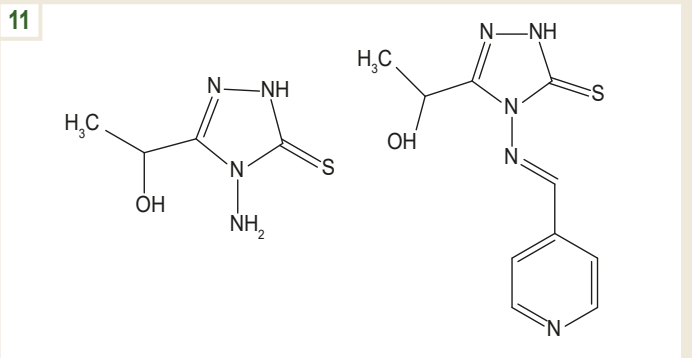

Fig. 11. Compounds (S)-1-(4-amino-5-mercapto-4*H*-1,2,4-triazol-3-yl)ethanol and (S)-1-(6-phenyl-7*H*-[1,2,4]triazolo[3,4-b][1,3,4]thiadiazine-3-yl)ethanol.

azole-3-(2*H*)-one demonstrated strong analgesic and anti-inflammatory activity in nociceptive and inflammatory models. This effect is due to a decrease in the sensitivity of nociceptors and blocking potential-dependent ion channels. It was noted that the studied compound significantly reduces the level of inflammatory biomarkers and reduces the formation of edema caused by formalin, by inhibiting the level of neuropeptides, histamine and proteinoids.

Pakistani scientists T. Azim et al. [22] approached the study of anti-inflammatory activity in their synthesized derivatives of 1,2,4-triazole with a fragment of 1,3,4-thiadiazine *(Fig. 11)* by determining anti-inflammatory, analgesic and antipyretic activity. Swiss albino mice and Wistar rats of both sexes were used for this purpose. Anti-inflammatory studies were evaluated on an animal model of acute inflammatory pain using the carrageenan paw edema model and the egg albumin-induced paw edema method. These models initiate two-phase release of inflammatory mediators. The antinociceptive activity of the synthesized compounds was also studied in several models: under the action of acetic acid (snag reflex), a model of heat-induced nociception, and formalin. The antipyretic activity of the compounds was evaluated by modeling hyperpyrexia in animals using yeast. The comparison drug in all cases was ibuprofen. According to the results, it was found that the studied compounds exhibit significant anti-inflammatory, analgesic and antipyretic activity. It was found that the maximum edema inhibition for the compound (S)-1-(4-amino-5-mercapto-4*H*-1,2,4-triazole-3-yl)ethanol is 91 %, compared with the reference drug ibuprofen 82 %, while (S)-1-(6-phenyl-7*H*-[1,2,4]

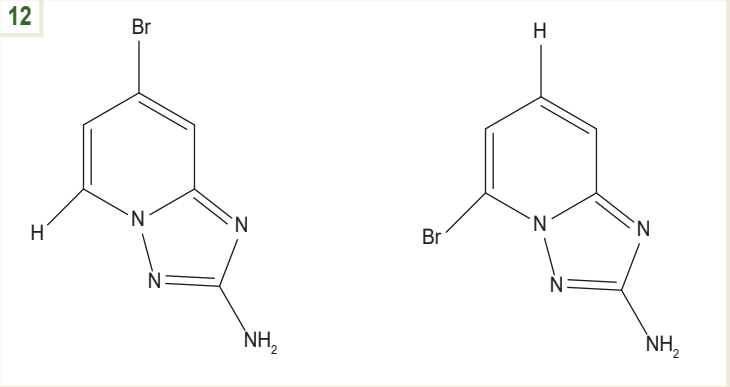

Fig. 12. Derivatives of [1,2,4]triazolo[1,5-a]pyridine: 7-bromo[1,2,4]triazolo[1,5-a]pyridine-2-amine and 5-bromo[1,2,4]triazolo[1,5-a]pyridine-2-amine.

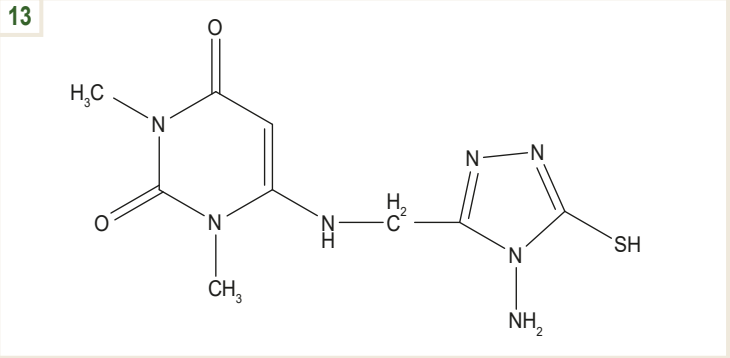

Fig. 13. 6-(((4-Amino-5-mercapto-4*H*-1,2,4-triazole-3-yl)methyl)amino)-1,3-dimethylpyrimidine-2,4(1*H*,3*H*)-dione.

triazolo[3,4-b][1,3,4]thiadiazine-3-yl)ethanol showed equipotential results than ibuprofen 81 %.

A considerable amount of literature data indicates significant antioxidant activity of 1,2,4-triazole derivatives [28,29].

For example, a group of domestic researchers studied the antioxidant activity of a series of [1,2,4]triazolo[1,5-a] pyridine derivatives. Which were obtained through the cyclization of intermediate products from the interaction of 2-aminopyridines and ethyl isothiocyanate carbonate [30]. The antioxidant activity of the substances was determined by inhibiting epinephrine oxidation under artificial oxidative stress *in vitro*. The intensity of free radical lipid oxidation was estimated spectrophotometrically by the formation of TBC-active products. Among the studied objects, the highest activity was found for 7-bromo[1,2,4]triazolo[1,5-a]pyridine-2-amine and 5-bromo[1,2,4]triazolo[1,5-a]pyridine-2-amine *(Fig. 12)*. Based on the research results, interesting structure-action dependencies have been established.

AL-Tamimi M. B. et al. synthesized heterocyclic derivatives containing fragments of 6-amino-1,3-methyluracilum and 1,2,4-triazole [31]. The antioxidant activity of the stable free radical DPPH was also studied for the obtained compounds. The synthesized compounds were determined at three different concentrations of 50, 100, and 150 micrograms/ml. The total antioxidant capacity was evaluated using the phosphomolybdenum method. This method is based on the reduction of colorless Mo (VI) to blue Mo (V) and the subsequent formation of green molybdenum phosphate (V). In both cases, ascorbic acid was used as a control. Quite positive results were obtained for all the synthesized compounds. But the highest activity was observed for 6-(((4-amino-5-mercapto-4*H*-1,2,4-triazole-3-yl)methyl) amino)-1,3-dimethylpyrimidine-2,4(1*H*,3*H*)-dione *(Fig. 13)*. It has also been proven that the effectiveness decreases with a decrease in concentration, so the best result was observed at a concentration of 150 mcg/ml.

Discussion

The obtained results indicate a significant influence of the chemical structure of 1,2,4-triazole derivatives on their biological activity, particularly their antitumor, anticonvulsant, antioxidant, antibacterial, and antifungal effects. Analysis revealed that the presence of electron-donating or electron-withdrawing substituents in the aromatic core significantly enhances the antitumor activity of the compounds.

The most promising among the studied compounds was 5-((4-(6-fluorobenzo[d]isoxazol-3-yl)piperidin-1-yl)methyl)-4-(4-nitrophenyl)-4*H*-1,2,4-triazole-3-thiol, which showed high activity against MCF-7 cells. DFT and molecular docking methods established a low energy gap, indicating its high reactivity. Studies of S- and S,N-bis-acylated nucleoside derivatives demonstrated that certain compounds exhibit significant cytotoxicity against Hep G2, MCF-7, and HCT116 liver cancer cells. Their mechanism of action is associated

with EGFR inhibition and tubulin polymerization suppression. Among a series of 5-methyl-4-aryl-3-(4-arylpiperazin-1-carbonyl)-4*H*-1,2,4-triazoles, the most potent antiproliferative activity was demonstrated by (4-(3,5-dimethoxyphenyl) piperazin-1-yl)(5-methyl-4-phenyl-4*H*-1,2,4-triazol-3-yl) methanone, which effectively inhibited tubulin polymerization and showed activity against SGC-7901, A549, and HeLa cancer cell lines.

In studies on the anticonvulsant activity of 4-amino-4*H*-1,2,4-triazole derivatives, it was found that the presence of electron-withdrawing groups, such as halogens, and heterocyclic aromatic fragments (e. g., indole) significantly enhances their effectiveness. Two compounds from this series outperformed the standard drug phenytoin, emphasizing the importance of structural features for pharmacological properties.

Investigations of 5-aryl-4-(chloroacetylamino)-3-mercapto-1,2,4-triazole derivatives revealed their high anticonvulsant activity, as confirmed by molecular docking and molecular dynamics simulations. These compounds effectively interacted with the GABA-A receptor, explaining their mechanism of action. These findings suggest that these compounds are promising candidates for further studies as antiepileptic drugs.

The antioxidant activity of [1,2,4]triazolo[1,5-a]pyridine derivatives and other heterocyclic compounds also depends on their chemical structure. The highest activity was observed in 7-bromo- and 5-bromo-[1,2,4]triazolo[1,5-a]pyridines, highlighting the importance of specific substituents in enhancing the antioxidant effect. The optimal concentration for achieving maximum activity was 150 μg/mL, indicating the need for precise dosage selection.

In studies of the antibacterial activity of "1,2,4-triazole-norfloxacin" hybrid compounds, it was found that they surpassed norfloxacin in effectiveness against both Gram-positive and Gram-negative bacteria. Molecular docking confirmed their optimal interaction with biological targets, with binding energies ranging from 9.4 kcal/mol to 9.7 kcal/mol. Additionally, the compounds did not induce hemolysis at a concentration of 64 μg/mL, demonstrating their good biocompatibility.

The antifungal and antibacterial activity of S-substituted 1,2,4-triazole-3-thiols also depended on the structure of the substituents. The most active compounds contained pyridine fragments and triazole rings, confirming the importance of these structural elements in enhancing biological activity.

Thus, the obtained results confirm that the chemical structure of 1,2,4-triazole derivatives plays a crucial role in determining their pharmacological properties. Optimization of molecular structures enables achieving high efficacy in combating various diseases, opening new prospects for the development of effective drugs.

Conclusions

1. Several structure-activity relationships have been established based on the analyzed literature sources.

2. It has been proven that 1,2,4-triazole derivatives exhibit a broad spectrum of biological activity, including antifungal, antimicrobial, anticancer, antibacterial, anticonvulsant, anti-inflammatory, and antioxidant effects.

3. Their potential as universal agents for the treatment of various diseases has been identified.

Prospects for further research. Due to their versatility, triazole derivatives can become the basis for the development of new drugs that can fight antibiotic resistance and infectious diseases, as well as provide support in the treatment of cancer.

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