UDC 547-305; 547-31/-39

BISCARBAMATES AND THIOCARBAMIDES IN BIOCHEMISTRY, MEDICINE AND MATERIALS SCIENCE

Kamola Khudoyberdieva
Assistant teacher at Navoi State University of Mining and Technologies PhD student
Bakhodir Mukhiddinov
Navoi State University of Mining and Technologies DSc. Professor
Abdukhamid Makhsumov
Tashkent Institute of Chemical Technologies DSc. Professor
Dilshod Akhtamov
Navoi State University of Mining and Technologies PhD Associate Professor

Abstract. Biscarbamates and thiocarbamides represent versatile classes of functional compounds with broad relevance across biochemistry, medicinal chemistry, and materials science. This review summarizes recent advances in the design, synthesis, biological evaluation, and applications of biscarbamate and thiocarbamide derivatives. Particular attention is given to enzyme inhibition, especially cholinesterase selectivity, where biscarbamates demonstrate high potency and stereoselectivity. The role of biscarbamate-modified polyethyleneimines in gene delivery is discussed, highlighting their reduced cytotoxicity and enhanced transfection efficiency for therapeutic applications. Computational modeling studies elucidating structure–activity relationships are reviewed, emphasizing the contribution of quantum and topological descriptors to predicting biological behavior. In addition, biscarbamates are examined as prodrug models and synthetic intermediates for heterocycle construction. The review further explores thiocarbamide derivatives as anticancer agents, biochemical probes, analytical materials, and metal-coordinating ligands, with a focus on their cytotoxic mechanisms and coordination chemistry. Collectively, these studies demonstrate the significant potential of biscarbamate and thiocarbamide scaffolds for the development of advanced biomedical and functional materials.

Keywords: Biscarbamates; thiocarbamides; enzyme inhibition; molecular modeling; anticancer activity; metal complexes

Аннотация. Бискарбаматы и тиокарбамиды представляют собой многофункциональные классы соединений, имеющие широкое применение в биохимии, медицинской химии и материаловедении. В данном обзоре обобщены современные исследования, посвящённые синтезу, биологической активности и практическому применению производных бискарбаматов и тиокарбамидов. Особое внимание уделено ингибированию ферментов, прежде всего холинэстераз, где бискарбаматы проявляют высокую

ISSN 3030-3907

селективность и стереоспецифичность. Рассмотрены бискарбамат-модифицированные полиэтиленимины как перспективные носители для генной доставки с пониженной цитотоксичностью и высокой трансфекционной активностью. Приведён анализ вычислительных исследований, направленных на установление взаимосвязей «структура–активность». Также обсуждается использование бискарбаматов в качестве моделей пролекарств и синтетических предшественников гетероциклических соединений. Отдельный раздел посвящён тиокарбамидам как противоопухолевым агентам, биохимическим зондом, аналитическим материалам и лигандам для комплексообразования с металлами. Представленные данные подтверждают высокий потенциал бискарбаматных и тиокарбамидных структур в разработке новых функциональных и биомедицинских материалов.

Ключевые слова: Бискарбаматы; тиокарбамиды; ингибирование ферментов; молекулярное моделирование; противоопухолевая активность; металлические комплексы

Annotatsiya. Bis-karbamatlar va tio-karbamidlar biokimyo, tibbiy kimyo va materialshunoslik sohalarida keng qo‘llaniladigan istiqbolli funksional birikmalar sinfiga kiradi. Ushbu sharh maqolada bis-karbamat va tio-karbamid hosilalarining sintezi, biologik faolligi va amaliy qo‘llanilishiga oid so‘nggi ilmiy tadqiqotlar tahlil qilinadi. Xususan, bis-karbamatlarning xolinesteraza fermentlarini selektiv va stereospetsifik inhibe qilishi muhim farmakologik jihat sifatida ko‘rib chiqiladi. Gen yetkazib berishda bis-karbamat bilan modifikatsiyalangan polietileniminlarning past sitotoksiklik va yuqori transfeksiya samaradorligiga ega ekanligi yoritiladi. Molekulyar modellashtirish asosida tuzilish–faollik munosabatlarini aniqlashga qaratilgan hisoblash ishlari tahlil qilinadi. Shuningdek, bis-karbamatlarning pro-dori modellarida va geterosiklik birikmalar sintezida oraliq modda sifatidagi roli muhokama qilinadi. Tio-karbamid hosilalarining esa saratonga qarshi faolligi, biokimyoviy zond sifatidagi ahamiyati, analitik materiallar va metall komplekslari hosil qilishdagi imkoniyatlari ko‘rsatib beriladi. Ushbu sharh bis-karbamat va tio-karbamid tuzilmalari asosida ilg‘or biomeditsina va funksional materiallar yaratish istiqbollarini namoyon etadi.

Kalit so‘zlar: Bis-karbamatlar; tiomochevinalar; ferment ingibitsiyasi; molekulyar modellashtirish; saratonga qarshi faollik; metall komplekslari

Introduction

Biscarbamates and thiocarbamides are important classes of functional compounds that have gained increasing attention due to their structural flexibility and broad applicability in biochemistry, medicinal chemistry, and materials science. Their molecular frameworks enable hydrogen bonding, metal

ISSN 3030-3907

coordination, and controlled chemical reactivity, making them attractive for the design of bioactive molecules and advanced functional materials.

Biscarbamates, containing two carbamate groups within a single structure, have shown significant potential in enzyme inhibition, gene delivery, prodrug development, and synthetic methodology. In particular, their selective inhibition of cholinesterase enzymes has provided valuable insights into structure–activity relationships relevant to neurological research. Moreover, biscarbamate-modified polymers, especially polyethyleneimine derivatives, have emerged as efficient non-viral gene carriers, offering improved transfection efficiency and reduced cytotoxicity compared to conventional systems.

Thiocarbamide derivatives are widely recognized for their diverse biological activities, including anticancer and enzyme-modulating effects, as well as their strong affinity for transition metals. Their ability to form stable metal complexes has expanded their applications in medicinal inorganic chemistry and nitric oxide delivery. Recent advances in molecular modeling have further enhanced understanding of the structure–activity relationships of both biscarbamates and thiocarbamides.

This review summarizes recent developments in the synthesis, biological activity, and functional applications of biscarbamates and thiocarbamides, highlighting their roles in enzyme inhibition, gene delivery, anticancer research, analytical chemistry, and metal coordination.

LITERATURE REVIEW

Biscarbamates in Enzyme Inhibition and Biochemical Applications

Biscarbamate compounds have demonstrated remarkable selectivity in enzyme inhibition, particularly toward cholinesterases, which are crucial targets in neurological and pharmacological research. Bosak et al. investigated the inhibition selectivity of metacarb and isocarb toward mouse acetylcholinesterase (AChE) and butyrylcholinesterase (BChE), revealing that these biscarbamates are exceptionally potent BChE inhibitors with inhibition rate constants ranging from 10^3 to 10^4 $M^{-1}s^{-1}$ [1]. The study demonstrated that metacarb and isocarb inhibited BChE 260 and 35 times faster than AChE, respectively, with the selective inhibition primarily dictated by two amino acid residues: leucine 286 from the acyl pocket and glutamine 119 from the peripheral site. Furthermore, both wild-type enzymes exhibited pronounced stereoselectivity for (R)-enantiomers of these biscarbamates, and the residues defining BChE selectivity also influenced the stereoselectivity of the enzymes. This work provides critical insights into structure-activity relationships and the molecular determinants of enzyme selectivity for biscarbamate inhibitors [1].

Biscarbamate-Modified Polyethyleneimine for Gene Delivery

ISSN 3030-3907

The development of biscarbamate-modified polyethyleneimine (PEI) has emerged as a promising strategy to overcome the cytotoxicity limitations associated with high molecular weight PEI while maintaining efficient gene delivery capabilities. Xu et al. reported a novel poly(ethylene imine) biscarbamate conjugate (PEIC) with low molecular weight (MW = 2800, Mn = 910) that exhibited orders of magnitude higher luciferase gene transfection activity compared to PEI of MW 2000 or 25,000 at optimal conditions [2]. This polycationic gene carrier was synthesized by reacting low molecular weight PEI (MW = 800) with 1,4-butanediol bis(chloroformate) to generate a copolymer containing biodegradable carbamate linkages. The PEIC condensed DNA at weight ratios above 1 to form polyplexes of 53–91 nm with zeta potentials of 20–24 mV, approximately half that of branched 25 kDa PEI. Notably, PEIC successfully transfected MeWo cells with large genes such as the 125 kb Varicella-Zoster viral gene, demonstrating its capacity for delivering therapeutically relevant large genetic constructs with reduced cytotoxicity [2].

Building upon this foundation, Xiang et al. further advanced the application of biscarbamate cross-linked low molecular weight PEI for therapeutic gene delivery in arthritis treatment [3]. Their study focused on delivering the interleukin-1 receptor antagonist (IL-1Ra) gene to synoviocytes, which are optimal targets for arthritis therapy. The biscarbamate cross-linked PEI (PEI-Bu) with Mn: 3278 and Mw: 4289 significantly reduced target cell apoptosis induced by polycationic transfection while maintaining DNA condensation capability comparable to PEI 25 kDa. The PEI-Bu demonstrated significantly higher transfection activity and lower cytotoxicity than PEI 25 kDa in delivering IL-1Ra gene to rat synoviocytes. The expressed IL-1Ra effectively suppressed the expression of metalloprotease 13 (MMP13), which is responsible for cartilage destruction regulated by IL-1β in arthritis. This work established PEI-Bu as a promising tool for gene therapy approaches in inflammatory joint diseases [3].

The broader context of PEI-based functional materials has been comprehensively reviewed by Fattahi et al., who highlighted the recent advances in PEI-based nanomaterials, their transfection efficiency, and toxicity profiles [7]. The review emphasized that cationic polymers, particularly polyethyleneimines, have attracted considerable interest for various industrial and biomedical applications due to their highly positive charges, acceptable physicochemical properties, and capacity for further modifications. The flexible polymeric chains, broad molecular weight distribution, and repetitive structural units of PEIs make their customization for functional composites feasible. Through purposeful functionalization or modification, specific beneficial attributes can be introduced to PEIs, enhancing their biocompatibility, service life, and distinct geometry. The

ISSN 3030-3907

review provided comprehensive coverage of PEI applications in biotechnology, medicine, and bioscience, including drug delivery, biosensing, gene delivery, imaging, and tissue engineering, thereby contextualizing the importance of biscarbamate modifications in advancing PEI-based biomedical technologies [7].

Molecular Modeling and Structure-Activity Relationships of Biscarbamate Derivatives

Computational approaches have proven invaluable in elucidating the mechanisms of action and structure-activity relationships of biscarbamate derivatives. Font et al. conducted a comprehensive molecular modeling study on a series of (diselanediyldibenzene-4,1-diylnide)biscarbamate derivatives exhibiting cytotoxic and antiproliferative activity against MCF-7 human breast cancer cell line, as well as radical scavenging properties against DPPH and ABTS radicals [4]. The study classified the compounds into two distinct groups based on their mechanisms of action: (a) aliphatic carbamates, for which activity was related to an initial nucleophilic attack on selenium atoms followed by release of alkyl N-(4-selanylphenyl) and N-(4-selenenophenyl)carbamate moieties, ultimately yielding 4-aminobenzeneselenol and 4-selenenoaniline as the active species; and (b) aromatic carbamates, which underwent preferential nucleophilic attack on the carbamate moiety to yield 4-[(4-aminophenyl)diselanyl]aniline as a common structural fragment with demonstrated cytotoxic activity. The study employed topological descriptors, quantum descriptors (including bond order, atomic charges, total valences, ionization potential, electron affinity, and HOMO/LUMO locations), and conformational analysis to establish connections between molecular structure and biological activity. This work demonstrated the utility of computational chemistry in predicting and rationalizing the biological activities of biscarbamate derivatives [4].

Biscarbamates as Prodrug Models and Synthetic Intermediates

The cyclization behavior of biscarbamates has been explored for prodrug design applications, where controlled release of active pharmaceutical ingredients can be achieved through structural modifications. Papot et al. investigated biscarbamates derived from 2-aminobenzylamines as models for alcohol prodrugs, examining the factors influencing their cyclization to cyclic ureas with concomitant alcohol liberation [5]. The study revealed that unsubstituted N-arylcarbamate derivatives did not cyclize under mild conditions (40°C), while substitution of the benzylic position with two methyl groups promoted slow cyclization. N-methylation of the N-aryl carbamate had a more pronounced effect on cyclization rates. The relative cyclization rates correlated well with barrier heights obtained from ab initio calculations, which suggested that the highest cyclization rate of N-methylated derivatives resulted from steric hindrance caused by the N-methyl

ISSN 3030-3907

substituent. This work provided fundamental insights into the structural requirements for designing biscarbamate-based prodrugs with tunable release kinetics [5].

In synthetic methodology, Kimura et al. demonstrated the utility of biscarbamates as precursors for heterocyclic synthesis through palladium-catalyzed transformations [6]. Their work reported the efficient synthesis of 4-ethenylidene-2-oxazolidinones via palladium-catalyzed aminocyclization of 2-butyn-1,4-diol biscarbamates in the presence of catalytic amounts of $Pd_2(dba)_3 \cdot CHCl_3$ (0.005 equiv) and triethylamine (0.1 equiv), yielding the target oxazolidinones in reasonable yields. Structural analysis revealed that the allenic three-carbon unit was not linearly aligned but considerably distorted (173.6°), and the enamine double bond exhibited reactivity toward unsaturated amides and methyl vinyl ketone. This methodology expanded the synthetic utility of biscarbamates as versatile building blocks for accessing structurally diverse heterocyclic compounds [6].

Thiocarbamide Derivatives: Anticancer Activity and Metal Coordination

Thiocarbamide derivatives have emerged as a significant class of compounds with diverse biological activities, particularly in anticancer research. Pandey and colleagues have conducted extensive investigations on the synthesis, structural characterization, and biological evaluation of various N,N′-disubstituted thiocarbamide derivatives. In one comprehensive study, Pandey et al. synthesized four trigonal planar copper(I) complexes with novel N,N′-disubstituted isobutoxycarbonyl thiocarbamide ligands, characterized by the general formula $[Cu(ROCONHCSNHR^1)_2Cl]$, where coordination occurred exclusively through thione sulfur atoms due to strong intramolecular hydrogen bonding (NH···OC) preventing coordination through carbonyl oxygen [8]. All complexes exhibited quasireversible redox behavior corresponding to Cu(I)/Cu(II) couples and displayed stronger inhibitory properties against five human cancer cell lines compared to the free ligands. Notably, complexes 3a, 4a, and 5a exhibited IC_{50} values lower than cisplatin against C13* cisplatin-resistant cell line. Comet assay tests demonstrated significant DNA damage across 2008, C13*, and IGROV-1 cell lines, and all complexes induced apoptosis by blocking cell cycle progression in G0/G1 phase, establishing these copper(I)-thiocarbamide complexes as promising anticancer agents [8].

Further expanding the structure-activity relationship studies, Pandey et al. synthesized and characterized two new N,N′-disubstituted thiocarbamide derivatives: N-(2-chloro-4-nitrophenyl)-N′-(phenoxycarbonyl) thiocarbamide and N-(2-chloro-4-nitrophenyl)-N′-(4-nitrobenzoyl) thiocarbamide [9]. Both crystal

ISSN 3030-3907

structures exhibited symmetrical and planar conformations with anti-periplanar orientation of CO and CS groups. The molecular structures and vibrational properties studied at the B3LYP/6-311G++(d,p) level of density functional theory corroborated experimental results. In vitro cytotoxicity screening against seven human cancer cell lines (cervical: 2008 and C13*; colorectal: HT29 and HCT116; ovarian: A2780, A2780/CP, and IGROV-1) revealed that compound 2 exhibited significant activity against all cell lines, while compound 1 demonstrated appreciable activity specifically against ovarian carcinoma cell lines. These findings highlighted the importance of substituent effects on the biological activity of thiocarbamide derivatives [9].*

In a series of related studies, Pandey's group synthesized eight N-thiophenoyl-N′-substituted phenyl thiocarbamide derivatives from thiophene-2-carbonyl isothiocyanate and various substituted aromatic primary amines [11]. Crystal structure analysis of a representative compound revealed a twisted conformation of the carbonyl and thiocarbonyl groups across the CN bond of the thiocarbamide moiety and offset face-to-face π–π stacking interactions between thiophene and benzene rings. In vitro cytotoxicity assays using seven human cancer cell lines identified compounds 1, 11, 12, and 13 as displaying promising inhibitory activity against all tested cell lines [11]. Additionally, Pandey et al. investigated N,N-diphenyl-N′-(biphenyl-4-carbonyl/4-chlorobenzoyl) thiocarbamides, employing Hirshfeld surface analysis to assess intermolecular interactions driving crystal structure formation [12]. Both compounds exhibited promising activity against cervical and IGROV-1 cancer cells, with cell cycle arrest at G0/G1 phase supported by DNA damage and apoptosis studies. The integration of crystallographic analysis, computational studies, and biological evaluation provided comprehensive insights into the anticancer potential of thiocarbamide derivatives [12].

Pandey et al. also reported the synthesis of five N,N′-substituted thiocarbamides bearing pentoxycarbonyl or 2,2,2-trichloroethoxycarbonyl substituents [13]. Crystal structures of representative compounds showed trans orientation of C=S and C=O groups across the C–N bond, with crystal packing featuring centrosymmetric dimers connected by N–H···S hydrogen bonds and offset face-to-face π–π stacking between naphthalene rings. In vitro cytotoxicity evaluation against five human carcinoma cell lines (2008, C13*, A2780, A2780/CP, and IGROV-1) demonstrated that compounds H_2L_2–H_2L_4 possessed IC_{50} values indicating them to be very promising anticancer agents. These systematic studies established thiocarbamide derivatives as a versatile scaffold for developing anticancer therapeutics [13].*

Thiocarbamides as Biochemical Probes and Analytical Tools

ISSN 3030-3907

Beyond their therapeutic applications, thiocarbamide derivatives have found utility as selective biochemical probes for enzyme characterization. Guo et al. investigated the use of thiocarbamides as selective substrate probes for isoforms of flavin-containing monooxygenases (FMO) [10]. The study measured the oxidation of thiourea, phenylthiourea, 1,3-diphenylthiourea, 1,3-bis-(3,4-dichlorophenyl)-2-thiourea, and 1,1-dibenzyl-3-phenyl-2-thiourea catalyzed by purified pig liver FMO-1 and microsomal fractions from various tissues and species. While purified FMO-1 exhibited essentially constant Vmax for all five thiocarbamides at saturating substrate concentrations, microsomal catalyzed reaction velocities varied with tissue, species, and the van der Waals surface area of the thiocarbamide substrate. Rat liver, rat kidney, and rabbit liver microsomes failed to catalyze detectable oxidation of thiocarbamides larger than 1,3-diphenylthiourea, while lung microsomes from female rabbits only accepted substrates smaller than 1,3-diphenylthiourea. Conversely, liver microsomes from chickens, pigs, and guinea pigs catalyzed oxidation of larger thiocarbamides, though rates decreased with increasing substrate size. Separation of guinea pig liver microsomal activities into three distinct fractions revealed different substrate specificities consistent with multiple FMO isoforms. This work established that size-differentiated thiocarbamides serve as useful probes for measuring FMO isoform activities in crude tissue preparations [10].

In analytical chemistry applications, Yu et al. developed a novel thiocarbamide conversion-based nitrogen-rich covalent organic framework (COF) coating for electro-enhanced solid-phase microextraction (EE-SPME) of bisphenols [14]. The thiocarbamide-linked COF coating (Thiocarbamide-TZ-DHTP) was fabricated through molecular design and post-synthetic thiocarbamide conversion, resulting in a material possessing abundant O, N, and S functional groups that endowed the coating with higher polarity and significantly enhanced electrochemical performance. When applied to EE-SPME of polar bisphenols coupled with gas chromatography-tandem mass spectrometry (GC-MS/MS), the method exhibited wide linear ranges (2.0–800.0 ng L^{-1}), excellent correlation coefficients (0.9985–0.9994), and low detection limits (0.1–2.0 ng L^{-1}). The established method was successfully applied to detection of trace bisphenols in tea beverages with satisfactory recoveries (81.6%–118.6%). This work demonstrated that thiocarbamide-based materials represent a feasible pathway for preparing COF coatings with excellent electrochemical performance and high polarity for analytical applications [14].

Metal Complexes of Thiocarbamide Derivatives

The coordination chemistry of thiocarbamide derivatives with transition metals has yielded compounds with unique properties and potential applications.

ISSN 3030-3907

Shmatko et al. synthesized and characterized three cationic dinitrosyl iron complexes (DNICs) with thiocarbamide derivatives: $[Fe(SC(NH_2)_2)_2(NO)_2]_2(Cl)(ClO_4)\cdot H_2O$, $[Fe(SC(NH_2)_2)_2(NO)_2]ClO_4$, and $[Fe(SC(NHCH_3)_2)_2(NO)_2]BF_4$ [15]. These complexes were synthesized by direct nitrosylation of acidic solutions containing ferrous salts and thiocarbamide derivatives. Comprehensive structural characterization by X-ray analysis, IR, Mössbauer, and EPR spectroscopy revealed that DNICs with unsubstituted thiourea exhibited structural and physicochemical features independent of counterion type. However, introduction of electron-donating substituents to the thiourea molecule resulted in a small shift of νNO in IR spectra, slight increase of δFe, and averaging of g-factor anisotropy. Compared to other DNIC types, cationic DNICs with thiocarbamide derivatives were characterized by increased positive charge on the NO group and higher electrophilic activity and nitrosylating ability, providing evidence that cationic DNICs function as highly effective NO donors. This work expanded the understanding of thiocarbamide-metal coordination chemistry and its implications for nitric oxide delivery applications [15].

CONCLUSION

Biscarbamates and thiocarbamides represent versatile and highly promising molecular scaffolds with significant relevance across biochemistry, medicinal chemistry, and materials science. The studies reviewed demonstrate that biscarbamates exhibit notable selectivity in enzyme inhibition, particularly toward cholinesterases, and play an important role in the development of efficient and less cytotoxic gene delivery systems. Thiocarbamide derivatives, in turn, display a broad spectrum of biological activities, including pronounced anticancer effects, and serve as effective ligands for transition metal coordination, enabling applications in medicinal inorganic chemistry and nitric oxide delivery.

Advances in molecular modeling and structure–activity relationship analysis have provided valuable insights into the mechanisms governing biological activity and selectivity, supporting the rational design of improved biscarbamate and thiocarbamide derivatives. In addition, emerging applications in analytical chemistry and functional materials highlight the expanding interdisciplinary importance of these compounds.

Overall, biscarbamates and thiocarbamides continue to offer substantial opportunities for the development of advanced bioactive molecules and functional materials. Future research focused on green synthesis approaches, targeted molecular design, and integrated experimental–computational strategies is expected to further enhance their applicability in biomedical and technological fields.

ISSN 3030-3907

REFERENCES

1. Bosak, A., Gazić Smilović, I., Štimac, A., Vinković, V., Šinko, G., & Kovarik, Z. (2013). Peripheral site and acyl pocket define selective inhibition of mouse butyrylcholinesterase by two biscarbamates. Archives of Biochemistry and Biophysics, 529(2), 140-145. https://doi.org/10.1016/j.abb.2012.11.012
2. Xu, S., Chen, M., Yao, Y., Zhang, Z., Jin, T., Huang, Y., & Zhu, H. (2008). Novel poly(ethylene imine) biscarbamate conjugate as an efficient and nontoxic gene delivery system. Journal of Controlled Release, 130(1), 64-68. https://doi.org/10.1016/j.jconrel.2008.04.025
3. Xiang, S., Su, J., Tong, H., Yang, F., Tong, W., Yuan, W., Wu, F., Wang, C., Jin, T., Dai, K., & Zhang, X. (2012). Biscarbamate cross-linked low molecular weight PEI for delivering IL-1 receptor antagonist gene to synoviocytes for arthritis therapy. Biomaterials, 33(27), 6520-6532. https://doi.org/10.1016/j.biomaterials.2012.05.044
4. Font, M., Plano, D., Sanmartín, C., & Palop, J. A. (2017). Topological and quantum molecular descriptors as effective tools for analyzing cytotoxic activity achieved by a series of (diselanediyldibenzene-4,1-diylnide)biscarbamate derivatives. Journal of Molecular Graphics and Modelling, 73, 62-73. https://doi.org/10.1016/j.jmgm.2017.01.016
5. Papot, S., Bachmann, C., Combaud, D., & Gesson, J.-P. (1999). Study of biscarbamates derived from 2-aminobenzylamines as models for alcohol prodrugs. Tetrahedron, 55(15), 4699-4708. https://doi.org/10.1016/S0040-4020(99)00139-8
6. Kimura, M., Wakamiya, Y., Horino, Y., & Tamaru, Y. (1997). Efficient synthesis of 4-ethenylidene-2-oxazolidinones via palladium-catalyzed aminocyclization of 2-butyn-1,4-diol biscarbamates. Tetrahedron Letters, 38(22), 3963-3966. https://doi.org/10.1016/S0040-4039(97)00790-9
7. Fattahi, N., Gorgannezhad, L., Farkhonde Masoule, S., Babanejad, N., Ramazani, A., Raoufi, M., Sharifikolouei, E., Foroumadi, A., & Khoobi, M. (2024). PEI-based functional materials: Fabrication techniques, properties, and biomedical applications. Advances in Colloid and Interface Science, 325, 103119. https://doi.org/10.1016/j.cis.2024.103119
8. Pandey, S. K., Pratap, S., Pokharia, S., Mishra, H., Marverti, G., Kaur, M., & Jasinski, J. P. (2019). Copper (I) complexes based on novel N, N′-disubstituted thiocarbamides: Synthesis, spectroscopic, in vitro cytotoxicity, DNA damage and G0/G1 cell cycle arrest studies. Inorganica Chimica Acta, 491, 105-117. https://doi.org/10.1016/j.ica.2019.04.007
9. Pandey, S. K., Pratap, S., Tiwari, M. K., Marverti, G., & Jasinski, J. P. (2019). Experimental and theoretical exploration of molecular structure and anticancer properties of two N, N′–disubstituted thiocarbamide derivatives. Journal of

ISSN 3030-3907

Molecular Structure, 1175, 963-970. https://doi.org/10.1016/j.molstruc.2018.08.040

10. Guo, W.-X. A., Poulsen, L. L., & Ziegler, D. M. (1992). Use of thiocarbamides as selective substrate probes for isoforms of flavin-containing monooxygenases. Biochemical Pharmacology, 44(10), 2029-2037. https://doi.org/10.1016/0006-2952(92)90106-S

11. Pandey, S. K., Pratap, S., Marverti, G., Kaur, M., & Jasinski, J. P. (2019). Synthesis, spectroscopic, crystal structure and in vitro cytotoxicity studies of N-thiophenoyl-N′-substituted phenyl thiocarbamide derivatives. Journal of Molecular Structure, 1180, 447-454. https://doi.org/10.1016/j.molstruc.2018.12.011

12. Pandey, S. K., Pratap, S., Rai, S. K., Marverti, G., Kaur, M., & Jasinski, J. P. (2019). Synthesis, characterization, Hirshfeld surface, cytotoxicity, DNA damage and cell cycle arrest studies of N, N-diphenyl-N'-(biphenyl-4-carbonyl/4-chlorobenzoyl) thiocarbamides. Journal of Molecular Structure, 1186, 333-344. https://doi.org/10.1016/j.molstruc.2019.03.057

13. Pandey, S. K., Pratap, S., Gozzi, G., Marverti, G., & Butcher, R. J. (2018). Synthesis, molecular structure exploration and in vitro cytotoxicity screening of five novel N, N′- disubstituted thiocarbamide derivatives. Phosphorus, Sulfur, and Silicon and the Related Elements, 193(8), 507-514. https://doi.org/10.1080/10426507.2018.1452234

14. Yu, Q., Zhang, W., Wang, J., Xie, S., Liao, B., Chen, H., Ding, Q., & Zhang, L. (2024). Thiocarbamide conversion-based nitrogen-rich covalent organic framework coatings for electro-enhanced solid-phase microextraction of bisphenols. Journal of Chromatography A, 1727, 465000. https://doi.org/10.1016/j.chroma.2024.465000

15. Shmatko, N. Yu., Korchagin, D. V., Shilov, G. V., Ovanesyan, N. S., Kulikov, A. V., Sanina, N. A., & Aldoshin, S. M. (2017). The cationic dinitrosyl iron complexes family with thiocarbamide derivatives: Synthesis, structure and properties in the solid state. Polyhedron, 137, 72-80. https://doi.org/10.1016/j.poly.2017.08.006

ISSN 3030-3907