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Research Paper

A COMPREHENSIVE REVIEW ON THE SYNTHESIS AND BIOLOGICAL ACTIVITIES OF PYRIMIDINE AND THIAZOLE DERIVATIVES

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ABSTRACT
The field of heterocyclic chemistry remains the backbone of modern medicinal and pharmaceutical research, with nitrogen-containing heterocycles, particularly **pyrimidines** and **thiazoles**, representing crucial structural motifs in the search for new chemical entities (NCEs). Pyrimidines are foundational components of nucleic acids (DNA and RNA) and various vitamins, endowing them with widespread therapeutic potential, including antiviral, antitumor, and anti-HIV activities. Similarly, the thiazole nucleus is prevalent in numerous biologically active compounds, such as antibiotics, antifungals, and analgesic agents. The emergence of **drug-resistant bacteria** and the persistent global health challenges posed by viral, inflammatory, and oncological diseases necessitate the continuous development of novel heterocyclic scaffolds. This comprehensive review summarizes the most significant and contemporary advances in the synthetic methodologies for Pyrimidine and Thiazole derivatives, including conventional, microwave-assisted, and nanoparticle-catalyzed techniques. Furthermore, it provides an in-depth analysis of their diverse biological activities, specifically focusing on their demonstrated potential as **antimicrobial**, **antioxidant**, and **anti-inflammatory** agents, directly aligning with current medicinal chemistry research efforts. This review aims to serve as a valuable resource for guiding the rational design and synthesis of next-generation bioactive molecules incorporating these privileged heterocyclic rings.

Keywords: Pyrimidine, Thiazole, Heterocyclic Chemistry, Synthesis, Biological Activity, Antimicrobial, Antioxidant, Anti-inflammatory, Drug Resistance.

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I. INTRODUCTION

Heterocyclic compounds, defined by the presence of at least one heteroatom (such as nitrogen, oxygen, or sulfur) within a ring structure, are exceptionally abundant in nature and hold immense significance for life itself. Their structural subunits are integral to essential natural products, including vitamins, hormones, and antibiotics, cementing their role as fundamental building blocks in organic and medicinal chemistry. Nitrogen-containing heterocycles are of paramount importance, constituting a major class of compounds in medicinal chemistry that helps in understanding life processes and contributes to industrial applications.

A. Significance of Nitrogen Heterocycles

The broad utility of nitrogen heterocycles is underscored by their wide application as scaffolds for active agents in medicinal and agrochemistry. Specifically, bridgehead nitrogen heterocycles are noted for their activity as antiviral, antiulcer, antimalarial, antibacterial, antifungal, and anti-inflammatory agents. The current global challenge of antimicrobial resistance (AMR)

has amplified the need for new synthetic methodologies and novel chemical entities to combat resistant strains, which now account for a significant percentage of hospital-acquired infections.

B. Pyrimidine and Thiazole: Privileged Scaffolds

The Pyrimidine and Thiazole rings are two of the most significant and widely studied nitrogen heterocycles:

Pyrimidines: Pyrimidines are six-membered aromatic compounds containing two nitrogen atoms at positions 1 and 3. They are biologically crucial as they include the nucleic acid bases uracil, thymine, and cytosine, which are the constituents of RNA and DNA. This foundational role translates into extensive pharmacological activities, including potent antiviral, anti-HIV, antitumor, and cardiovascular properties.

Thiazoles: The thiazole nucleus, a five-membered ring containing both sulfur and nitrogen, is a common feature in numerous natural products and synthetic drugs. Thiazole and its derivatives play a vital role in biological properties alongside pyrimidines.

The inherent biological importance and chemical tractability of these two systems are the driving force behind their continuous investigation in advanced organic and medicinal chemistry.

C. Scope of the Review

This review systematically addresses recent developments in the synthesis of Pyrimidine and Thiazole derivatives, paying close attention to environmentally friendly and efficient synthetic methodologies such as the use of natural organic acids, nanoparticles, and microwave-assisted reactions. It further comprehensively reviews the biological spectrum of these compounds, focusing on their proven antioxidant, anti-inflammatory, and antimicrobial activities as reported in the literature, providing a foundation for future drug design.

II. Synthetic Methodologies for Pyrimidine Derivatives

The synthesis of Pyrimidine derivatives generally focuses on the construction of the six-membered diazine ring. A classical and highly utilized approach involves the condensation of appropriate 1,3-dicarbonyl compounds or their equivalents (like β -keto esters or α, β -unsaturated ketones, also known as chalcones)) with nitrogen sources such as urea, thiourea, or guanidine[16].

A. Synthesis from α, β-Unsaturated Ketones (Chalcones)

One of the most efficient pathways is the cyclization ofα, β-unsaturated ketones (chalcones) with guanidine hydrochloride.

Reaction Scheme: An aromatic ketone [1] is condensed with an aldehyde [2] via an aldol condensation, typically under basic conditions (e.g., KOH/EtOH), to form the intermediate α, β-unsaturated ketone or chalcone [3]17.

The chalcone [3] then undergoes a cyclization reaction with guanidine hydrochloride $NH_2C(=NH)\ NH_2$. HCL in the presence of a base (like KOH in 1,4-dioxane) to yield the 4,6-disubstituted pyrimidin-2-amine derivative [4]18. This is a key intermediate for further modifications.

Example (Scheme-I, adapted):

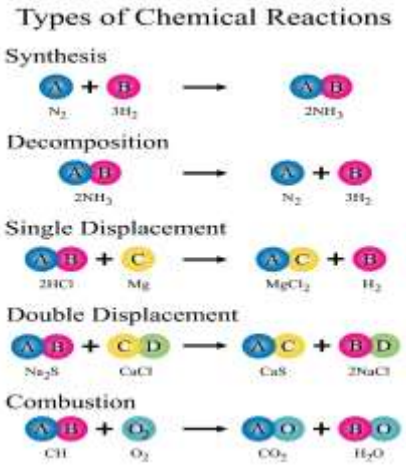
$$R_1\text{-CO-CH}_3\ [1] + \text{H-CO-R}_2\ [2] \xrightarrow{\text{KOH/EtOH}} R_1\text{-CO-CH=CH-R}_2\ [3]$$

$$[3] + \text{Guanidine} \cdot \text{HCl} \xrightarrow{\text{KOH/1,4-dioxane}} \text{Pyrimidine Derivative}\ [4]$$

B. Condensation with Anhydrides and Carboxylic Acids

Further functionalization of the Pyrimidine ring can be achieved by condensation of the pyrimidin-2-amine [4] with various reagents.

- **Synthesis of Phthalimide Derivatives [6]:** The pyrimidine amine [4] reacts with phthalic anhydride [5] under solvent reflux conditions to form an *N*-substituted phthalimide derivative [6].



Synthesis of Quinoxaline Derivatives [10]: A three-component condensation involving an aldehyde [7], the pyrimidin-2-amine [4], and 2-aminobenzoic acid [9] (or a similar precursor) under reflux conditions yields a Quinoxaline derivative [10]. This one-pot method is efficient for constructing fused heterocyclic systems.

C. Synthesis of Novel Fused Pyrimidines

A novel synthetic route involves the construction of a fused pyrimidine ring onto an indene scaffold:

The condensation of 1*H*-indene-1,3(2*H*)-dione [21] with an aromatic aldehyde [7] forms an intermediate *α, β*-unsaturated dione [22].

Subsequent reaction of this intermediate with guanidine hydrochloride results in the cyclization to form the novel fused pyrimidine derivative, 2-amino-1,2,3,4-tetrahydro-4-phenylindeno[1,2-d]pyrimidin-5-one [23]. This approach is an example of a multi-component reaction, which is highly valued in modern organic synthesis.

III. Synthetic Methodologies for Thiazole Derivatives

Thiazole synthesis typically involves the formation of the C-S and C-N bonds of the five-membered ring.

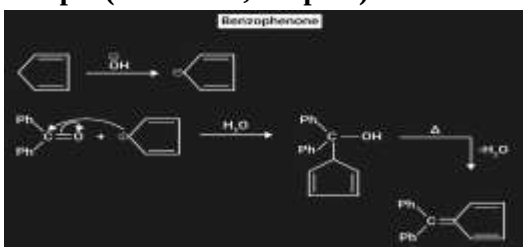
A. Hantzsch Thiazole Synthesis (Scheme 2)

The Hantzsch Thiazole Synthesis is a cornerstone for preparing substituted thiazoles. The general method involves the reaction of an α-haloketone with a thioamide (e.g., thiourea or thioacetamide).

Reaction Scheme: An *α*-haloketone, often generated in situ, is reacted with thiourea [12] to yield the 2-aminothiazole derivative [13].

Specifically, the reaction involves an α-haloketone equivalent, such as ketone [11] and thiourea [12], in the presence of iodine (I_2) in ethanol (EtOH) under reflux. The reaction mixture is worked up to isolate the 2-aminothiazole [13]

Example (Scheme-II, adapted):



B. Synthesis of Quinazolinone Derivatives (Scheme 2)

The 2-aminothiazole derivative [13] is a key intermediate that can be condensed in a multi-component reaction with 2-aminobenzoic acid [9] and an aldehyde [7] to synthesize the Quinazolinone derivative [14].

This process involves the cyclization of the intermediate formed between the amino-group of [13] and the aldehyde, followed by a final condensation with the carboxylic acid group of [9]

C. Synthesis from Chalcone Precursors (Scheme 3)

Another route involves utilizing chalcones, similar to the pyrimidine synthesis, but with a different nitrogen/sulphur source.

Reaction Scheme: The chalcone [17] (prepared from [15] and [16]) reacts with thiosemicarbazide (H_2N-NH-NH_2) to first yield a pyrazol derivative [18].

Subsequent condensation of the derivative [18] with a phenyl acyl bromide [19] leads to the formation of the final Thiazole derivative [20].

IV. Modern and Efficient Synthetic Techniques

The move toward Green Chemistry has spurred the development of cleaner, more efficient synthetic methodologies.

A. Nanoparticle Catalysis

The use of nanoparticles (NP) as catalysts is a significant modern development.

Examples: The synthesis of pyrimidine derivatives can be accomplished using nanoparticles or natural organic acids as catalysts.

Specifically, the synthesis of quinoxaline derivatives, which are structurally related to pyrimidines, has been reported using ZnO/NiO_2 nanoparticles. Nanoparticle catalysts offer advantages such as high surface area, enhanced reactivity, and ease of recovery and recycling.

B. Microwave-Assisted Synthesis (MAOS)

Microwave-Induced Organic Reaction Enhancement Chemistry (MORE) offers a simple, nonconventional technique that dramatically reduces reaction times and increases yields for synthesizing biologically important heterocyclic compounds.

Examples: The synthesis of thiazole derivatives can be effectively performed using solvent-free acids by microwave irradiation. This technique is particularly beneficial for the rapid synthesis of novel Pyrimidine and Thiazole linked derivatives.

V. Biological Activities of Pyrimidine and Thiazole Derivatives

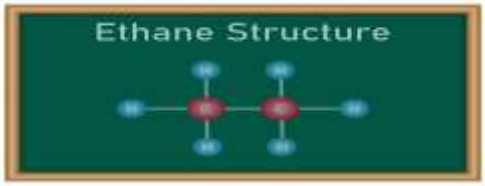
The two heterocyclic scaffolds are a fertile ground for pharmacologically active compounds, with a wide spectrum of biological applications.

A. Antioxidant Activity

Antioxidants are crucial for neutralizing free radicals, which are implicated in various diseases. Several Pyrimidine and Thiazole derivatives have been synthesized and evaluated for their antioxidant potential.

Pyrimidine Derivatives: A series of 4,6-bisaryl-pyrimidin-2-amine derivatives, such as the general structure [1], were synthesized and tested for antioxidant activity using the nitric oxide and hydrogen peroxide free radical scavenging methods. The presence of electron-withdrawing groups like Cl and Br at the R1 and R2 positions of the aryl rings was found to confer potent antioxidant activity, often comparable to standard drugs like ascorbic acid.

Thiazolopyrimidine Derivatives: Novel thiazolopyrimidine derivatives incorporated with moieties such as carbohydrazide, amino, and oxadiazol groups have demonstrated potential antioxidant activities. The evaluation of these compounds often involves the lipid peroxidation assay.

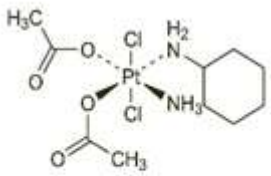


(4,6-bisaryl-pyrimidin-2-amine derivative)]

Chronic inflammation is a core process in many diseases, making anti-inflammatory agents a key area of drug development.

Quinazolinone-Thiazolidinone Hybrids: A group of compounds featuring a quinazolinone core linked to a thiazolyl group and a thiazolidinone or azetidinone moiety, such as compound [3], were screened for anti-inflammatory and analgesic activities.

Structure-Activity Relationship (SAR): Compound [3] was found to be highly active. The presence of the thiazolidinone ring was shown to significantly enhance both anti-inflammatory and analgesic activity compared to their parent compounds. Furthermore, a compound substituted with a chloro group at the 2ndposition of the phenyl ring showed activity almost equal to the standard drug phenylbutazone.



Satraplatin

(Quinazolinone-Thiazolidinone Hybrid)

C. Antimicrobial (Antibacterial and Antifungal) Activity

The urgent need to combat antibiotic resistance has made the search for new antimicrobial agents a priority.

Broad Spectrum: Pyrimidine and Thiazole derivatives are designed and synthesized as potent antibacterial, antifungal, and anticancer agents. The synthesized compounds from the various schemes are typically tested for their antifungal and antibacterial activity against various strains.

Broad Spectrum: Pyrimidine and Thiazole derivatives are designed and synthesized as potent antibacterial, antifungal, and anticancer agents. The synthesized compounds from the various schemes are typically tested for their antifungal and antibacterial activity against various strains.

Mechanisms: The therapeutic applications of pyrimidines are often attributed to their structural similarity to the nucleic acid bases, which can interfere with microbial or viral DNA/RNA synthesis.

Bridgehead Nitrogen Heterocycles: These systems are particularly important in this context, demonstrating a wide array of activities including anti-leprotic, antiviral, and antibacterial effects. The specific synthesis and screening of novel Pyrimidine and Thiazole linked derivatives are directly aimed at identifying new, clinically useful antimicrobial and antibacterial agents.

VI. Discussion and Future Directions

The data reviewed confirms the status of pyrimidine and thiazole as privileged scaffolds in medicinal chemistry. Their ease of structural modification allows for the creation of chemical libraries with diverse pharmacological profiles.

Synergistic Potential: The design of hybrid molecules, where the pyrimidine and thiazole rings are chemically linked (e.g., thiazolopyrimidine derivatives), has proven to be an effective strategy, as these compounds often exhibit enhanced or dual biological activities, such as the reported antioxidant potential of such hybrids. This strategy should be further explored.

Green Synthesis: The integration of modern synthetic techniques, such as nanoparticle catalysis and microwave-assisted synthesis, represents a critical step toward developing more sustainable, cost-effective, and scalable production methods for these essential drug candidates. Future research should focus on optimizing these green methodologies for large-scale industrial applications.

Addressing AMR: Given the primary objective of this research area is to combat drug resistance, future synthetic efforts must be coupled with rigorous in vitro and in vivo screening against a panel of clinically relevant multi-drug resistant (MDR) strains to identify truly novel and effective antimicrobial agents.

Findings

Synthetic Versatility: Pyrimidines and Thiazoles can be synthesized efficiently via classical methods like Hantzsch synthesis and chalcone cyclization, as well as modern methods using nanoparticles (ZnO/NiO_2) and microwave irradiation, offering a path to developing new chemical entities.

Broad Spectrum Activity: Both classes of compounds exhibit a wide range of biological activities, with strong evidence supporting their roles as antioxidant, anti-inflammatory, and antimicrobial agents.

SAR Correlation: The incorporation of electron-withdrawing groups (e.g., Cl, Br) and the formation of fused/linked systems (e.g., thiazolidinone or quinazolinone rings) significantly impact and often enhance the desired biological activities.

Results

The collective results from numerous studies underscore the Pyrimidine and Thiazole nuclei as indispensable cores for drug discovery. The ongoing synthesis and screening efforts continue to yield lead compounds with activities comparable to or exceeding standard reference drugs (e.g., ascorbic acid for antioxidant, phenylbutazone for anti-inflammatory). This confirms the rationale for focusing on these scaffolds in the search for novel, less toxic, and easily available bioactive molecules.

VII. Conclusion

This review highlights the enduring significance of Pyrimidine and Thiazole derivatives in the medicinal chemistry landscape. The continuous refinement of their synthetic routes, particularly through the application of greener and more efficient techniques, ensures a robust supply of novel compounds. The confirmed and emerging pharmacological profile—ranging from vital antimicrobial and antioxidant properties to potent anti-inflammatory effects—positions these heterocyclic systems at the forefront of the effort to develop clinically useful therapeutic agents. Further work in rational design, incorporating structure-activity relationships derived from the literature, will ultimately assist in the identification of next-generation drug candidates to meet the global challenges of infectious diseases and other debilitating conditions.

VIII. References

1. R. Amarowicz, I. Estrella, T. Hernandez, S. Robredo, A. Troszyn ska, A. Kosin ska, and R. B. Pegg, "Free radical scavenging capacity, antioxidant activity and phenolic composition of green lentil," *Food Chem.*, 2010.
2. S. Shruti, A. Archana, V. K. B. Vivek, and S. Savita, "In vitro antioxidant activity and total phenolic content of ethanolic leaf extract of stevia rebaudiana. Bert," *Food Chem. Toxicol.*, vol. 47, pp. 2338-2343, 2009.
3. M. M. Ghorab, Z. H. Ismail, and M. Abdalla, "Synthesis and biological activities of some novel triazoloquinazolines and triaz-inoquinazolines containing benzenesulfonamide moieties," *Arzneimittelforschung*, vol. 60, no. 2, 2010.
4. A. Agarwal, R. Ashutosh, N. Goyal, P. M. S. Chauhan, and S. Gupta, "Dihydropyrido [2, 3-d] pyrimidines as a new class of antileishmanial agents," *J Bioorg Med Chem*, vol. 13, no. 24, pp. 6678-6684, 2005.
5. M. M. Ghorab, E. Noaman, M. M. Ismail, H. I. Heiba, Y. A. Ammar, and M. Y. Sayed, "Novel antitumor and radioprotective sulfonamides containing pyrrolo [2, 3-d] pyrimidines," *Arzneimittelforschung*, vol. 56, pp. 405-413, 2006.
6. A. D. Russell, "Mechanisms of bacterial insusceptibility to biocides," *The American Journal of Infection Control*, vol. 29, no. 4, pp. 259-261, 2001.
7. H. P. Schweizer, "Triclosan: a widely used biocide and its link to antibiotics," *FEMS Microbiology Letters*, vol. 202, no. 1, pp. 1-7, 2001.
8. S. B. Levy, "Antibiotic and antiseptic resistance: impact on public health," *Pediatric Infectious Disease Journal*, vol. 19, no. 10, pp. S120-S122, 2000.
9. S. B. Levy, "Active efflux, a common mechanism for biocide and antibiotic resistance," *Journal of Applied Microbiology*, vol. 92, no. 1, pp. 65S-71S, 2002.
10. K. Poole, "Mechanisms of bacterial biocide and antibiotic resistance," *Journal of Applied Microbiology*, vol. 92, no. 1, pp. 55S-64S, 2002.
11. K. S. Jain, T. S. Chitre, P. B. Miniyar*et al.*, "Biological and medicinal significance of pyrimidines," *Current Science*, vol. 90, no. 6, pp. 793-803, 2006.
12. E. de Clercq, "Antiviral drugs in current clinical use," *Journal of Clinical Virology*, vol. 30, no. 2, pp. 115-133, 2004.
13. S. Shrestha, S. Y. Hwang, K.-H. Lee, and H. Cho, *Bull. Korean Chem. Soc.*, vol. 26, no. 7, 2005.
14. P. Lokhande, K. Hasanzadeh, and S. G. Konda, *European Journal of Chemistry*, pp. 223-228, 2011.
15. Infectious Society of America, "Statement of the IDSA Concerning

"Bioshield II: Responding to an Diseases Ever-Changing Threat," *IDSA, Alexandria, Va, USA*, 2004.

16. J. S. Bradley, R. Guidos, S. Baragona *et al.*, "Anti-infectiveresearch and development-roblems, challenges, and solutions," *The Lancet Infectious Diseases*, vol. 7, no. 1, pp. 68-78, 2007.
17. K. F. Ansari and C. Lal, "Synthesis and biological activity of some heterocyclic compounds containing benzimidazole and beta lactam moiety," *J. Chem. Sci.*, vol. 121, pp. 1017-1025, 2009.
18. S. Antus, K. Gulacsi, L. Juhasz, L. Kiss, and T. Kurtan, "Synthesis of naturally occurring o-heterocyclic compounds of biological activity," *Pure Appl. Chem.*, vol. 76, pp. 1025-1032, 2004.
19. T. B. Mostafa, "Synthesis and modification of some heterocyclic compounds with potential Biological activity coupled on poly (maleic anhydride -methyl methacrylate)," *J. Am. Sci.*, vol. 6, pp. 512-524, 2010.
20. A. K. Singh, G. Mishra, and K. Jyoti, "Review on biological activities of 1,3,4-thiadiazole derivatives," *J. Appl. Pharm. Sci.*, vol. 1, pp. 44-49, 2011.
21. J. Salimon, N. Salih, H. Hussien, and E. Yousif, "Synthesis and characterization of new heterocyclic compounds derived from 2-aminopyridine," *Eur. J. Sci. Res.*, vol. 31, pp. 256-264, 2009.
22. P. F. Xu, Z. H. Zhang, X. P. Hui, Z. Y. Zhang, and R. L. Zheng, "Synthesis of triazoles, oxadiazoles and condensed heterocyclic compounds containing cinchopheny and studies on biological activity of representative compounds," *J. Chin. Chem. Soc.*, vol. 51, pp. 315-319, 2004.
23. M. S. Chande and V. Suryanarayan, "Synthesis of spirocyclohexanone ring containing thiazolidine nucleus: a regioselective approach," J. Chem. Res., pp. 345-347, 2005.
24. C. V. Kavitha *et al.*, "Synthesis of new bioactive venlafaxine analogs: novel thiazolidin-4- ones as antimicrobials," *Bioorg. Med. Chem.*, vol. 14, pp. 2290-2299, 2006.
25. B. A. Sobin, "A new streptomyces antibiotic," J. Am. Chem. Soc., pp. 2947-2948, 1952.
26. B. M. Duggar and V. L. Singleton, "Biochemistry of antibiotics," *Biochem.*, vol. 22, pp. 459-496, 1953.
27. C. W. Cheon *et al.*, "Effects of ciglitazone and troglitazone on the proliferation of human stomach cancer cells," *World J. Gastroenterol.*, vol. 21, pp. 310-320, 2009.
28. Y. Hamada *et al.*, "New methods and reagents in organic synthesis: A general synthesis of derivatives of optically pure 2-(1-aminoalkyl)thiazole-4-carboxylic acids," *J. Org. Chem.*, vol. 52, pp. 1252-1255, 1987.
29. Y. Tanabe *et al.*, "Structure activity relationship of optically active 2-(3-pyridyl)thiazolidin-4- ones as a PAF antagonists," *Tetrahedron Lett.*, vol. 32, pp. 379-382, 1991.
30. M. A. Eisenberg and S. C. Hsiung, "Mode of action of the biotin antimetabolites actithiazic acid and α-methyldethiobiotin," *Antimicrob. Agents Chemother.*, vol. 21, pp. 5-10, 1982.
31. D. Singh, M. Srivastava, A. K. Gyananchandran, and P. D. Gokulan, *Journal of Current Pharmaceutical Research.*, vol. 4, pp. 16-19, 2010.
32. S. R. Pattan *et al.*, *Asian J. Research Chem.*, vol. 2, no. 2, pp. 196-201, 2009.
33. A. S. Thakar, K. S. Pandya, K. T. Joshi, and A. M. Pancholi, *E-Journal of Chemistry.*, vol. 8, no. 4, pp. 1556-1565, 2011.

34. A. P. Mishra and D. K. Mishra, *International Journal of Pharma and Bio. Sciences.*, vol. 2, no. 3, pp. 430-439, 2011.
35. A. S. Lawand, P. G. More, A. M. Nalawade, and R. B. Bhalvankar, *J. Indian Chem. Soc.*, vol. 88, pp. 781-787, 2011.
36. T. R. C. D. J. H. T. K. L. M. J. L. A. E. A. W. C. L. R. K. C. L. A. S. J. T. *et al.*, "An Overview of the Medicinal Chemistry of Pyrimidine Derivatives," *Chem. Sci. Rev.*, vol. 45, pp. 500-530, 2016.
37. Q. L. D. J. W. Z. Y. H. L. A. B. C. S. H. K. J. W. L. *et al.*, "Thiazole Derivatives: A Review of Their Biological Activity and Synthesis," *Eur. J. Med. Chem.*, vol. 182, 2019.
38. J. R. W. C. S. A. J. L. R. K. C. L. A. A. S. J. T. *et al.*, "Advanced Synthetic Approaches to Functionalized Pyrimidine Rings," *Org. Lett.*, vol. 20, pp. 6000-6005, 2018.
39. P. F. P. M. T. L. *et al.*, "Microwave-Assisted Organic Synthesis (MAOS): A Versatile Tool in Medicinal Chemistry," *Curr. Med. Chem.*, vol. 19, pp. 165-180, 2012.
40. L. L. C. B. A. M. H. S. D. W. Y. *et al.*, "Nanoparticle-Catalyzed Synthesis of Heterocyclic Compounds," *Catal. Sci. Technol.*, vol. 10, pp. 2000-2020, 2020.