Synthesis, reactions, and applications of pyrimidine derivatives

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\textbf{Abstract}

Pyrimidine compounds continue to attract great interest in the field of organic synthesis due to their various chemical and biological applications observed, especially in recent times. As a result, this review covering some periods from 1957 to 2021 has been prepared to discuss some of the structural pathways of these compounds as well as some of their interactions and applications.

\textbf{1. Introduction}

Pyrimidines ("m-diazine") were known as the breakdown products of uric acid. The first pyrimidine derivative to be isolated was alloxan (5,5-dihydroxypyrimidine-2,4,6(1\textsubscript{H},3\textsubscript{H},5\textsubscript{H})-trione) (Fig. 1) in 1818 by Brugnatelli, oxidizing uric acid with nitric acid.\textsuperscript{1} Pyrimidines (Fig. 1) are the heterocyclic aromatic compounds similar to benzene and pyridine containing two nitrogen atoms at positions 1 and 3 of the six-membered rings. Pyrimidine has one axis of symmetry about the 2-5 axis; it has three different pairs of bond lengths and four different bond angles. Accordingly, in \textsuperscript{1}H and \textsuperscript{13}CNMR spectra, the \textsuperscript{1}H and \textsuperscript{13}C nuclei are found at three different chemical shifts. Symmetry is lost by unequal substitution at the 4 or/and 6 position.\textsuperscript{2} Heterocyclic containing pyrimidine moiety are of great interest because they constitute an important class of natural and non-natural products, many of which exhibit useful biological activities and clinical applications.\textsuperscript{3,4} Heterocyclic compounds containing pyrimidine moiety are gaining the focus in recent research due to their wide range of biological activities such as anti-inflammatory, antioxidant, antimicrobial, antitumor, antiviral, antidepressant, antiplatelet, antihypertensive and herbicidal. Additionally, thienopyrimidine-containing compounds are found in many pharmaceutical medications and as natural products.
2. Synthesis of pyrimidine and its compounds

2.1 From ethyl cyanoacetate.

Kambe et al. synthesized 5-cyano-4-oxo-6-alkyl(aryl)-2-thioxo-1,2,3,4-tetrahydropyrimidine derivatives (4a-d) by the reaction of a mixture of ethyl cyanoacetate (1), aldehydes (2) and thiourea (3) in the presence of potassium carbonate as a catalyst under condensation reaction (Scheme 1).5

![Scheme 1](image1)

Scheme 1. Synthesis of pyrimidine derivatives from ethyl cyanoacetate.

2.2 From acetyl acetone.

Lewis et al. synthesized the pyrimidine derivatives (7) by the reaction of acetyl acetone (5) and benzaldehyde in the presence of two eq. of ammonium acetate to afford (Z)-4-iminopent-2-en-2-amine intermediate (6), then a process of dehydrogenation occurs from the latter to afford the pyrimidine derivative (7) (Scheme 2).6

![Scheme 2](image2)

Scheme 2. Synthesis of pyrimidine derivatives from acetyl acetone.
2.3 From 1,3-diaminopropane.

One of the most important methods to synthesize tetrahydro pyrimidine derivatives from 1,3-diaminopropane was reported by Fischer et al. and developed by Grath et al. They reacted 1,3-diaminopropane (8) with formaldehyde, diethyl carbonate and carboxylic acid to afford the corresponding pyrimidine derivatives (9a-c) (Scheme 3).7,8

![Scheme 3. Synthesis of pyrimidine derivatives from 1,3-diaminopropane](image)

2.4 From diacetyl ketene.

Gordeev et al. reported the synthesis of some pyrimidine derivatives from the reaction of 3-(amino(substituted thio)methylene)pentane-2,4-dione (10, 11) with isocyanates in the absence of bases to give 4-alkylthio-5-acetyl-l-alkyl(aryl)-6-methyl-1H-pyrimidin-2-ones (12a-e) in good yields (Scheme 4).9

![Scheme 4. Synthesis of pyrimidine derivatives from diacetyl ketene](image)
2.5 From enaminonitrile.

Synthesis of heterosystems containing pyrimidine moiety was reported by Briel et al. remains one of the most versatile methods. In their method, enaminonitrile (13) was treated with CS<sub>2</sub> in the presence of sodium methoxide to give pyrimidinethione derivative (14) (Scheme 5).<sup>10</sup>

![Scheme 5. Synthesis of pyrimidine derivatives from enaminonitrile](image)

2.6 From alkynes.

Müller’s group developed a method to synthesize pyrimidines by the reaction of acid chlorides (15) and terminal alkynes (16) under Sonogashira conditions. It represented a straightforward one-pot three-components method to produce 2,4-di- and 2,4,6-trisubstituted pyrimidines (17a,b) in moderate to good yields (Scheme 6).<sup>11</sup>

![Scheme 6. Synthesis of pyrimidine derivatives from alkynes](image)

2.7 From (trimethylsilyl) acetylene.

Müller et al. developed a method to synthesize 2,4-substituted pyrimidines. By the reaction of (hetero)aryl chlorides (15) with (trimethylsilyl)-acetylene (18) in the presence of triethylamine, THF and methyl cyanide under Sonogashira coupling conditions to afford disubstituted pyrimidines (19a,b) (Scheme 7).<sup>12</sup>

![Scheme 7. Synthesis of pyrimidine derivatives from trimethylsilyl acetylene](image)
2.8 From α-methyl or α-methylene ketones.

Lejon et al. developed a palladium-catalyzed synthesis of pyrimidines (21a-c) by the reaction of α-methyl or α-methylene ketones (20) with formamide in the presence of palladium (II) acetate and triphenylphosphine (Scheme 8).  

\[
\text{Formamide/indohenezene} \xrightarrow{\text{Pd(OAc)}_2/\text{PPh}_3} \text{N} \quad \text{N} \quad \text{R} \quad \text{R} \\
21a: R= \text{[structure]} \quad 21b: R= \text{[structure]} \quad 21c: R= \text{[structure]}
\]

Scheme 8. Synthesis of pyrimidine derivatives from α-methyl or α-methylene ketones

2.9 From (hetero)aryl iodides

Müller and coworkers developed a method for synthesis of pyrimidine derivatives (23a,b). By the reaction of (hetero)aryl iodides (22) and terminal alkynes (16) in THF at room temperature under 1 atom of carbon monoxide in the presence of 2 eq. of triethylamine and catalytic amounts of \([\text{Pd(PPh}_3)_2\text{Cl}_2]\) and Cul for 48 h followed by addition of the amidinium salts in the presence of 2.5 eq. of sodium carbonate in acetonitrile/water gave the 2,4,6-tri substituted pyrimidines (23a,b) (Scheme 9).  

\[
\text{Ar-I} + \equiv = \text{R}_1 \quad \xrightarrow{(i) \text{Pd(PPh}_3)_2\text{Cl}_2 (5 \text{ mol\%})} \quad \xrightarrow{(ii) \text{Cul (2 mol\%)}}, \text{THF, rt, 1h} \quad \xrightarrow{(iii) \text{EtN (2 eq.)}, 1 \text{atom CO, rt, 48 h}} \quad \xrightarrow{(iv) \text{HN, Na}_2\text{CO}_3, \text{CH}_3\text{CNH}_2\text{O}} \quad \text{R}_1 \quad \text{R}_2 \quad \text{N} \quad \text{N} \\
23a: \text{Ar=} \text{[structure]}, \text{R}_1=\text{nBu}, \text{R}_2=\text{[structure]} \quad 23b: \text{Ar=} \text{[structure]}, \text{R}_1=\text{CH}_3, \text{R}_2=\text{[structure]}
\]

Scheme 9. Synthesis of 2,4,6-tri substituted pyrimidines

2.10 From dihydropyrimidinones.

Pyrimidine derivatives (25a-c) were synthesized by Yamamoto et al. through the oxidation of dihydropyrimidinones (24) in the presence of CuCl₂, K₂CO₃ and CH₂Cl₂. The suspension was heated at 38 °C and treated with tert-butyl hydroperoxide (70% aqueous solution) over 120 min with vigorous agitation to afford the target compounds (Scheme 10).  

\[
\text{COOMe} \quad \text{NH} \quad \text{NH} \quad \text{O} \quad \text{COOMe} \\
(24) \quad \text{R}_1 \quad \text{R}_2 \quad \text{R}_1 \quad \text{R}_2 \\
(25 \text{a-c}) \\
25a: \text{R}_1=\text{Ph}, \text{R}_2=\text{CH}_3 \quad 25b: \text{R}_1=\text{C}_6\text{H}_4\text{p-OCH}_3, \text{R}_2=\text{CH}_3 \quad 25c: \text{R}_1=\text{C}_6\text{H}_4\text{p-F}, \text{R}_2=\text{CH}_3
\]

Scheme 10. Synthesis of pyrimidine derivatives from dihydropyrimidinones
2.11 From iodochromone.

Langer’s group reported on the synthesis of 2,4,6-trisubstituted pyrimidine derivatives by ring transformation reactions of 2-alkylidene tetrahydrofurans with amidines. However, Hu et al. developed an efficient method to generate a diversified pyrimidine library via a sequential one-pot reaction of iodochromone (26), arylboronic acid (27), and amidine by Suzuki coupling and condensation to give the pyrimidine derivatives (28) (Scheme 11).\(^{16,17}\)

Scheme 11. Synthesis of pyrimidine derivatives from iodochromone

2.12 From aryl halides.

Stonehouse et al. described a palladium-catalyzed four-component reaction for the generation of pyrimidines, which was a one-pot process. In their reaction, a wide range of aryl halides (22), terminal alkynes (16), molybdenumhexa carbonyl and amidines (29) were shown to be an efficient method for the construction of highly substituted pyrimidines (30) (Scheme 12).\(^ {18}\)

Scheme 12. Synthesis of pyrimidine derivatives from aryl halides

2.13 From sulfonyl azides.

A one-pot synthesis of N-sulfonyl-2-alkylidene-1,2,3,4-tetrahydropyrimidines (33) via a highly selective and copper-catalyzed multi-components reaction of sulfonyl azides (31), terminal alkynes (16), and \(\alpha,\beta\)-unsaturated imines (32) was developed by Wang et al. (Scheme 13).\(^ {19}\)

Scheme 13. Synthesis of pyrimidine derivatives from sulfonyl azides

2.14 From functionalized enamines.

Konakahara et al. reported a ZnCl\(_2\)-catalyzed three-components coupling reaction involving a variety of functionalized enamines (34), triethyl orthoformate (35), and ammonium acetate (36), which led to the production of 4,5-disubstituted pyrimidine derivatives (37) (Scheme 14).\(^ {20}\)
2.15 From orthoester

Sasada groups developed procedures for the synthesis of tri- and tetra substituted pyrimidine derivatives (40a,b) in good to excellent yields by the reaction of enamidine (38) with an orthoester (39) in toluene or xylene at 110 °C, for 15-96 h (Scheme 15).21

2.16 From benzonitrile

Obora et al. established a practical method for the preparation of poly substituted pyrimidine derivatives (43a-e), which gave moderate to good yields. The reaction was successful using terminal alkynes with n-octyl, phenyl, and cyclohexyl groups (41) and benzonitrile (42). In the presence of NbCl₅ as a catalyst at 60 °C for around 22 h (Scheme 16).22

2.17 From malononitrile.

Rostamizadeh et al. reported a one-pot, three-component reaction to synthesize pyrimidine derivatives (46a-d). By the reaction of aldehyde (2), malononitrile (44), and benzamidine hydrochloride (45) were synthesis transformed in the presence of magnetic nano Fe₃O₄ particles as the catalyst under solvent-free conditions. The pyrimidine-5-carbonitrile derivatives (46a-d) in their method were prepared in good yields (Scheme 17).23
2.18 From N-methyl-N-(phenylethynyl)methane sulfonamide.

Karad et al. reported on gold-catalyzed cycloadditions reaction between N-methyl-N-(phenylethynyl)methanesulfonamide (47) and benzonitrile (42) to afford monomeric 4-aminopyrimidines (48), which were commonly found in many bioactive molecules (Scheme 18).24

Scheme 18.

Scheme 18. Synthesis of monomeric 4-aminopyrimidines (48)

2.19 From 1-(naphthalene-1-yl)-1,3-butadiyne.

Xing et al. developed a facile and efficient synthesis of 4-iminopyrimidines (52a-d) via a copper-catalyzed three-component reaction. In that method a mixture of 1-(naphthalene-1-yl)-1,3-butadiyne (49), tosylazide (50) and substituted imidamides (51) was stirred continually for 3 h at room temperature in the presence CuCl at room temperature under N₂ atmosphere and Et₃N (Scheme 19).25

Scheme 19.

Scheme 19. Synthesis of pyrimidine derivatives from naphthalene butadiyne
2.20 From N-(substituted carbamothioyl) benzimidamides.

Shafiee and coworkers reported a simple procedure for the synthesis of a series of poly functionalized pyrimidines (54a-c). In the presence of CuBr/Et3N in DMF at 80 °C via the reaction between N-(substituted carbamothioyl) benzimidamides (53) and malononitrile (44), good yields of the desired products were observed (Scheme 20).26-28

![Scheme 20](image)

**Scheme 20.** Synthesis of poly functionalized pyrimidines

2.21 From β-enaminonamide intermediates.

Qomi et al. reported that a method for the synthesis of some pyrimidines derivatives (56a-c) in good to excellent yields. In their method the intermediates (55a-c) were condensed with guanidine derivatives under reflux with ethanol in the presence of sodium ethoxide to form the corresponding tricyclic derivatives (56a-c) (Scheme 21).29

![Scheme 21](image)

**Scheme 21.** Synthesis of pyrimidine derivatives from β-enaminonamide intermediates

2.22 From acetoacetanilide.

Venkatesan et al. reported that an efficient and simple method for the synthesis of pyrimidine-5-carboxamides (59a-d) using a mixture of substituted acetoacetanilide (57), aldehyde (2), urea or thiourea (58) and UO2(NO3)2·6H2O as a catalyst under conventional and microwave irradiation. The synthesis of dihydropyrimidine using uranyl nitrate had produced many advantages such as easy work up, short reaction time and high yields (Scheme 22).30

![Scheme 22](image)

**Scheme 22.** Synthesis of pyrimidine derivatives from acetoacetanilide
2.23 From N-arylbenzimidoyl chlorides

Zielinski et al. reported the synthesis of 2-phenylquinazolin-4-amine by the reaction of N-arylbenzimidoyl chlorides (60) with cyanamide at room temperature to afford the corresponding intermediates (61). Finally, after several hours of heating in benzene in the presence of the Lewis acid catalyst TiCl₄, compound (61) underwent cyclization to give the final product (62) (Scheme 23).³¹

![Scheme 23. Synthesis of pyrimidine derivatives from N-arylbenzimidoyl chlorides](image)

2.24 From 2-aminobenzimidazole

Sharma et al. reported the synthesis of ethyl 2-methyl-4-(2-nitrophenyl)-1,4-dihydrobenzo[4,5]imidazo[1,2-a]pyrimidine-3-carboxylate (66) by the reaction of 2-aminobenzimidazole (63), 2-nitrobenzaldehyde (64) and ethyl acetoacetate (65) in the presence of ZnONPs as catalyst for 40 min (Scheme 24).³²

![Scheme 24. Synthesis of pyrimidine derivatives from 2-aminobenzimidazole](image)

3. Reactions of pyrimidine and its compounds

3.1 Electrophilic substitution's reaction.

Electrophilic substitutions like halogenation, Vilsmeier formylation, nitration and alkylation, were demonstrated in thieno[2,3-d]pyrimidines (I) and thieno[3,4-d]pyrimidines (III) involved position 6 and eq. position 7, respectively, which is typical of thiophene itself and suggested a weak influence of annulation with the pyrimidine ring. A different situation was observed for electrophilic substitution in thieno[3,2-d]pyrimidines (II), where the influence of annulation of the pyrimidine ring was stronger than the effect of orientation of the sulfur atom in the thiophene ring and, consequently, the attack occurred at position 7 (Fig. 2).

![Fig. 2. The active positions for electrophilic substitutions in thienopyrimidines derivatives](image)

3.2 Halogenation

(a) Bromination of compounds (67a,b) with mild brominating agent, (NBS), in DMF afforded 4-amino-6-bromo-2-substitutedthieno[2,3-d]pyrimidines (68a,b) (Scheme 25).³³
(b) 6-Bromo-1,3-dimethylthieno[2,3-d]pyrimidine-2,4(1H,3H)-dione (70) was formed by the addition of a solution of bromine dissolved in acetic acid to thienopyrimidine (69) (Scheme 26).34

3.3 Nitration

Thieno[2,3-d]pyrimidine (69) was reacted with a solution of fuming nitric acid in concentrated sulfuric acid to afford 6-nitro-1,3-dimethyl thieno[2,3-d] pyrimidine-2,4 (1H,3H)-dione (71) (Scheme 27).34

3.4 Vilsmeier-Haack reaction.

Reaction of compound (69) with phosphorus oxychloride and DMF under Vilsmeier-Haack condition gave 6-formyl-1,3-dimethylthieno[2,3-d]pyrimidine -2,4(1H,3H)-dione (72) (Scheme 28).34
3.5 Alkylation

2-(2-Chloro-4-morpholinothieno[2,3-d]pyrimidin-6-yl)propan-2-ol (74) was obtained from treatment of (2-chloro-4-morpholin-4-yl)thieno[3,2-d]pyrimidine (73) with n-BuLi followed by addition of dry acetone (Scheme 29).35

3.6 Ring opening of the thiophene ring

(a) Ethyl 3-(2-ethoxy-2-oxoethyl)-2,5-dimethyl-4-oxo-3,4-dihydrothieno[3,4-d]pyrimidine-7-carboxylate (75) was underwent desulfurization under the action of raney nickel to yield ethyl 4-(ethoxycarbonylmethyl)-5-ethyl-2-methyl-6-oxo-1,6-dihydropyrimidin-1-yl-acetate (77) (Scheme 30).36

(b) When compound (78) was allowed to react with hydrazine hydrate, gave unexpectedly a ring opened compound, 2,4-dihydrazino-6-(3-methoxy phenyl)-pyrimidine-5-carbonitrile (79) (Scheme 31).37

3.7 From amino-carboxamide

Tolba et al. succeeded in synthesizing some heterocyclic thienopyrimidine compounds (81-85) starting from amino-carboxamide (80).38 Also, the photophysical properties of the selected compounds were investigated at different concentrations of solutions and at high solid-state temperatures and were theoretically confirmed by density functional theory calculations. The studied dyes showed the properties of AIE with spectral shapes related to the overall structure with a quantitative yield of 10.8%. The pigment powder emission efficiency is attributed to the incorporation of the double twisted spindle aryl moieties into the molten heterogeneous cycles. These dyes also showed high thermal stability and strong
antimicrobial activities against many strains of bacteria and fungi. Besides, the cytotoxicity of the novel compounds was estimated against the Caco-2 cell line (Scheme 32).  

Scheme 32. Reactions of thienopyrimidine derivative (80) with various reagents

4. Pharmacological Activities of pyrimidine and its derivatives

The chemistry of pyrimidine derivatives plays an important role in the field of drugs, agriculture chemicals, and many biological processes. In recent decades, a large number of pharmacological studies have been done on pyrimidines and their derivative. However, still more research is required in order to necessity the biological compounds. Numerous methods for the synthesis of pyrimidine and their diverse reaction generate an enormous scope in the field of medicinal chemistry.  

Pyrimidines have received much attention in medicinal chemistry due to their biological activities and therapeutic applications (Fig. 3). One possible reason for their biological activities is the presence of pyrimidine base as nucleobases, which are essential building blocks of nucleic acids, DNA and RNA. Due to the significant biological activity of pyrimidine derivatives, the synthesis of this class of compounds plays an attractive scaffold in the medicinal chemistry and drug discovering.

Fig. 3. Some drugs containing pyrimidine nucleus

Sacchi et al.  synthesized a series of imidazo[1,2-a]pyrimidine-2-carboxylic acid and acetic acid analogs (91, 92a,b) and tested them for anti-inflammatory activity. Almost all the carboxylic acid derivatives showed a remarkable anti-inflammatory activity (Fig. 4).
On the other side, 4-(4-aminothieno[2,3-d]pyrimidin-5-ylamino)-1,5-dimethyl-2-phenyl-1,2-dihydropyrazol-3-one (93) was synthesized by Aly et al. and evaluated the antimicrobial activity of the synthesized compound against some strain of bacteria and fungi and exhibited high activity (Fig. 5).43

Several derivatives containing thieno[2,3-d]pyrimidine ring systems were prepared from 2-amino-4,5-dihydronaphtho[2,1-b]thiophene-1-carbonitrile. The prepared products were tested for antiviral activity against H5N1 virus [A/chicken/Egypt/1/2006 (H5N1)] by determination of both EC50 and LD50 and confirmed by plaque reduction assay on MDCK cells. Compounds (94 and 95) showed the highest effect compared with the other reference compounds (Fig. 6).44

Rashmi et al. reported on the synthesis of some 4,5-unsubstituted thieno[2,3-d] pyrimidine derivatives (96a,b) and evaluated their antioxidant activity using DPPH radical scavenging activity, hydrogen peroxide scavenging activity and nitric oxide scavenging activity. The tasted compounds showed moderate free radical scavengering activity (Fig. 7).45

El-Gazzar et al. reported the synthesis of some thieno[3,2-d]pyrimidine derivatives and evaluated for their anticancer activity against three human cancer cell lines, including the human breast adenocarcinoma cell line (MCF-7), cervical carcinoma cell line (HeLa) and colonic carcinoma cell line (HCT-116). In addition, the other's reported that compounds (97-99) were nearly as active as doxorubicin (reference drug) whereas compounds (100,101) exhibited marked growth.
inhibition, but still lower than doxorubicin (Fig. 8). All these findings confirm the importance of organic compounds in different fields.47-87

Fig. 8. Compounds (97-101) as antitumor agents

5. Conclusions

This review described the several efficient synthetic approaches and reactions of pyrimidine and their related compounds. The synthetic strategies of these pyrimidine derivatives designated in this review comprise the construction of the pyrimidine moiety starting with various organic reagents of them where indicated. The preparatory methods presented in this review are easy to apply, use simple raw materials, and include more environmentally friendly reaction conditions. We hope this review is useful and appealing to researchers in the field of heterocyclic synthesis. Also, it can help them to prepare novel heterocycles containing pyrimidine moiety with promising biological activities.

References

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