Heterocyclic Letters
Vol. 14| No.2|457-467|Feb-April|2024
ISSN : (print) 2231–3087 / (online) 2230-9632
CODEN: HLEEAI
http://heteroletters.org

EXPEDITIOUS SYNTHESIS OF OXYGEN AND SULFUR HETEROCYCLES BY MICROWAVE

Aparna Das* and Bimal Krishna Banik*

Department of Mathematics and Natural Sciences, College of Sciences and Human Studies, Prince Mohammad Bin Fahd University, Al Khobar 31952, Kingdom of Saudi Arabia; email: aparnadasam@gmail.com; bimalbanik10@gmail.com; bbanik@pmu.edu.sa

Introduction

The oxygen- and sulfur-heterocycles are crucial compounds due to their medicinal activities. Microwave-mediated preparation of O-heterocycles and S-heterocycles is an important objective. Many of these reactions are environmentally benign, fast, high yielding and economical. For simplicity, no structures of the compounds are given in this perspective. All references for the synthesis of oxygen and sulfur-heterocyclic compounds are mentioned. In continuation of our diverse research program, we have identified numerous methods for publications in journals and books. We believe readers will find the strategy useful as described herein in their research program. This type of style may open up a new possibility of publishing papers in a concise way.

Oxygen-containing molecules

A few oxygen-containing molecules are mentioned here. Xanthenes are important compounds [1]. For example, benzoxanthenes have anticancer [2], antibacterial [3], and glycoprotein inhibiting properties [4]. Xanthenes are also used in laser methods [5], fluorescent materials [6] and dyes [7].

Ashok et al. described a route for the synthesis of pyranoxanthenes using a one-pot multi-component reaction [8]. The reaction of aromatic aldehyde, substituted chroman-7-ol, and cyclohexanedione was conducted in a microwave in the presence acetic acid. It was shown that microwave heating was the best choice for this purpose. These compounds were tested for antimicrobial and antioxidant properties. A few molecules demonstrated good antibacterial properties. The nitro compound showed good antibacterial activity.

An efficient method for the synthesis of octahydroxanthene by condensation of dimethyl-cyclohexanedione and aldehyde in the presence of an ionic liquid using microwave was conducted [9].

Chavez et al. studied microwave-medaited bismuth triiodide-mediated synthesis of octahydroxanthenes [10]. Microwave-assisted reaction of cyclohexanedione with aldehyde in the presence of bismuth salts was performed. Other bismuth (III) salts were tested. Bismuth nitrate, bismuth halides, bismuth oxide, and bismuth subnitrate were used. Bismuth iodide produced the best yields.

Furans have numerous medicinal properties: anticancer, antibiotics, antifungal, antidepressant, and pain killing. Ashok et al. synthesized a few chroman-4-one fused benzofurans through a cyclization method in a microwave [11]. Chalcone on ring cyclization with butanone produced benzofuran. These molecules were tested to find their *in vitro* antibacterial activity against two Gram-positive bacteria (*Staphylococcus aureus* and *Bacillus faecalis*) and two Gram-negative strains (*Escherichia coli* and *Klebsiella pneumonia*). Two compounds showed antibacterial properties. These compounds were tested for antifungal activity against pathogenic fungi (*Fusarium oxysporum* and *Aspergillus flavus*) and the results are impressive.

Microwave-mediated procedure was employed for a one-pot method for the synthesis of isobenzofuran-ones with sulphamic acid [12]. Isobenzofuran-one was synthesized using 2-carboxybenzaldehyde and many ketones. A reaction of 2-carboxybenzaldehyde, ketone and sulphamic acid on irradiation by microwave produced the pure compound.

The microwave-induced one-pot procedure between furan and furanone were conducted by triethyamine-mediated cascade reaction of furan, benzofuran carboxylic acids and cyanopropargylic alcohols [13]. The product furanone was obtained. The reaction failed to proceed without Et_3N or other tertiary amines.

An aurone has a benzofuran connected to a benzylidene system in position 2. Aurones have many medicinal activities as antioxidant [14], antitumor [15, 16], antiparasitic [17, 18] antiviral, antidiabetic [19], neuroprotective [20], CDK1 inhibitor [21], antinociceptive [22], antimutagenic [23], antioxidant [24], and antidiabetic [25, 26]. The microwave-induced method for the preparation of 2-arylidene-2H-furo[2,3-f]chromen-3(7H)-ones was reported [27]. Microwave-induce Claisen–Schmidt reaction of 1-(5-hydroxy-2H-chromen-6-yl)ethanone and aromatic aldehydes in presence of KOH gave 3-(aryl)-1-(5-hydroxy-2H-chromen-6-yl)prop-2-en-1-one. These molecules were screened for antioxidant and antimicrobial activity. The results showed a high radical scavenging potential and better antimicrobial activity than the available compounds in this area.

The preparation of benzofuran-3(2H)-ones using microwave was investigated by Hu et al. [28]. The products were obtained in satisfactory yields.

5-Ethoxymethylfurfural (EMF) was synthesized from D-fructose in the presence of eutectic solvents (DESs) as promoters in a microwave oven [29]. The choline chloride-oxalic acid produced the best yield of D-fructose. The reaction of D-fructose with ethanol in the presence of DESs gave to 5-Hydroxymethyl furfural (HMF) which on reaction produced 5-Ethoxymethylfurfural (EMF).

Coumarin, an important type of organic molecule was first realized by Vogel in 1820 [30, 31]. In 1868, Perkin prepared coumarin [32]. Many coumarins are medicinally active [33-38]. Microwave-assisted method was used for the synthesis of cinnamic acid and coumarin [39]. The preparation started with an aldehyde as a substrate and a Wittig reagent. A reaction between aldehyde and ylide was conducted to prepare cinnamic acid derivatives. Microwave-induced synthesis of 3-aryl-furo[3,2-c]coumarins was accomplished by two methods [40]. Numerous 3-aryl-furo[3,2-c]coumarins were synthesized reacting 4-hydroxy coumarins with 2-aryl-1-nitro ethenes. A number of 3-aryl-furo[3,2-c]coumarins were synthesized reacting 4-hydroxy coumarins with aroylmethyl bromides following Feist–Benary's method.

These molecules were screened against Gram-negative bacteria (*Escherichia coli*), Gram-positive bacteria (*Bacillus subtilis)* and fungi *Candida albican.* The agar cup diffusion method was chosen for the determination of the antimicrobial activity. These molecules have good activity against Gram-negative bacteria. Importantly, not a single compoundfrom this group showed superior activity against *Bacillus subtilis* and *Candida albicans*.

Osthole, a natural coumarin has antiarrhythmia, antifungal, antidiabetic, antirumor, antiinflammatory, antiosteoporosis, hepatoprotection, and neuroprotection activities [41-49]. Microwave-assisted synthesis of ostholes by the reaction of 4-hydroxycoumarins and beta-ketoesters was available [50]. These compounds were screened against six phytopathogenic fungi and a few of them showed activity. Many condensed coumarin analogues, pyrano[3,2-c]chromene-2,5-diones were synthesized following microwave-induced procedure [51]. These molecules were screened for their antifungal activity. A few of the coumarin derivatives have antifungal activities.

Numerous hydroxycoumarins were synthesized by microwave-assisted process [52]. On reaction of coumarins with chloroacetonitrile and potassium carbonate resulted in O-substituted cyanomethoxy derivatives. The molecules having coumarin and chromene systems, called pyranocoumarins are challenging and pyranocoumarins demonstrated anti-HIV activity.

Ashok et al. showed the synthesis of this type of compound using microwave-mediated process [53].These compounds were screened for their antimicrobial activity. Some of them was active against fungal and bacterial strains.

Microwave-assisted palladium-induced Heck reaction was conducted on quercetin derivative with terminal alkenes [54]. Synthesis of substituted 1,4-dioxines via oxiranes and diazo compounds was known. These molecules exhibited urease inhibition and cytotoxic activity.

Sulfur containing molecules are biologically crucial [55-57]. Microwave-assited parallel synthesis of a library of N-aroyl and N-aryl thioureas were performed [58].

Microwave-mediated copper-assisted ring expansions of heterocycles with diazo-dicarbonyl molecules were studied [59]. This method described a simple procedure for the preparation of dioxins. Preparation of oxathiines by a ring enlargement of thiiranes and diazo compounds was described.

A few thiophene hydrazones were synthesized by microwave-induced method [60]. A few chemists prepared sulfanyl-substituted chromenones. Anjaiah et al. demonstrated microwave-assisted synthesis of 3-arylsulfanyl-chromen-2-ones by condensation of arenesulfonohydrazides with hydroxy-chromenone using iodine [61]. These molecules were tested for *in vitro* antimicrobial activity and good results were observed.

Various 1-(arylthio)naphthalen-2-ols were synthesized by condensation of naphthalen-2-ol with diaryldisulfanes using iodine and microwave [62]. These compounds were tested to identify their antibacterial and antifungal properties.

A microwave-induced method for the preparation of hetaryl and ferrocenyl substituted thioketones was described [63]. Microwave-mediated one-pot preparation of oxathiolanes was conducted by Kermani [64]. The 2-(nitromethylidene)-1,3-oxathiolane was prepared using nitromethane, CS_2, oxirane, and Et_3N. Some substituted hetaryl thioketones reacted with diazoketones in a microwave [65]. The phenyl(thiophen-2-yl) thioketone on reaction with 2-diazo-1,2-diphenylethanone in the presence of microwave produced 2,4,5-triphenyl-2-(thiophen-2-yl)-1,3-oxathiole and 3,3,4-triphenyl-4-(thiophen-2-yl)thietan-2-one. Similar studies with ferrocenyl compounds under microwave irradiation were not successful. But, these reacted with diazopropanone and 2-diazo-ethanone with $LiClO_4$ to give α,β-unsaturated ketones.

Benzoselenophene moiety is regarded as a bioisoster of benzofuran, naphthalene, benzothiophene, and indole system [66]. Benzoselenophenes have received attention because of their uses in medicines [67-70]. Arsenyan et al. reported microwave-induced palladium-promoted cyanation of 3-bromo-2-(1-hydroxyalkyl)benzo[b]selenophenes [71]. The starting molecule was activated in a microwave irradiation and catalyst Pd(PPh3)4.

Various phosphinic, phosphonic esters, and phosphine oxides were synthesized by P–C-mediated reactions of aryl- and vinyl halides with phosphites, phosphinates and phosphine oxides using microwave [73]. Microwaveinduced method was applied for the synthesis of arylphosphonates using cyclodiphosphazane-Pd [74]. Keglevich et al. demonstrated that Hirao reaction proceeds with excess P-reagents [75]. Jablonkai and Keglevich showed a ligand-free Carbon–Phosphorous coupling method [76]. A reaction of halo benzoic acids (iodo and bromo), and diaryl phosphine oxides was conducted in a microwave. Microwave-assisted preparation of azidoalkylphosphonates through nucleophilic reaction of the bromoalkylphosphonates with sodium azide was reported [77] .

An isomerization of 7-substituted cycloheptatrienes was performed with DABCO and t-BuOK [78]. Following this method, allyltriphenylphosphonium bromide was prepared by reaction of triphenylphosphine and allyl bromide.

The AuNP-supported Gd complex was an effective promoter for the acetylation of alcohols and phenol [79]. Microwave-assisted acetylation of alcohols and phenol was performed. Microwave-assisted Cannizzaro reaction was reported to convert aldehydes to carboxylic acids [80]. A microwave-mediated Claisen-Schmidt method for the synthesis of α,β-unsaturated ketones was known [81]. The preparation of 2,3-dihydroxypropyl decanoate was accomplished by esterification of decanoic acid with glycidol and glycerol carbonate [82]. Monoglycerides were synthesized from decanoic acid, and glycerol carbonate or glycidol in the presence of TBAI.

The α-aryl malonates are important for the sythesis of heterocycles [83]. The reaction of aromatic halides with diethyl malonate using $Cu(OTf)_2$, Cs_2CO_3, and 2-picolinic acid was performed for this purpose.

Conclusion

The significance of microwave-mediated reactions for the synthesis of numerous organic compounds is discussed here. Many microwave-induced processes toward oxygen and sulfur molecules are described. These methods have numerous advantages: solvent-free reaction, reduction of reaction time, catalytic nature, economical and rapid process. Because of these advantages, researchers engaged in drug discovery use microwave-induced procedures.

Acknowledgements

AD and BKB are grateful to Prince Mohammad Bin Fahd University for support. BKB is also grateful to US NIH, US NCI and Kleberg Foundation of Texas for finance support.

References

1. (a) S. Shi, Y. Zhang, K. Huang, S. Liu, Y. Zhao, Application of preparative high-speed counter-current chromatography for separation and purification of lignans from Taraxacum mongolicum, Food Chem. 108 (2008) 402-406; (b) F. Zhang, L. Li, S. Niu, Y. Si, L. Guo, X. Jiang, Y. Che, A thiopyranchromenone and other chromone derivatives from an Endolichenic fungus, Preussia Africana, J. Nat. Prod. 75 (2012) 230-237.
2. Z.M. Yang, J. Huang, J.K. Qin, Z.K. Dai, W.L. Lan, G.F. Su, H. Tang, F. Yang, Design, synthesis and biological evaluation of novel 1-hydroxyl-3-aminoalkoxy xanthone derivatives as potent anticancer agents, Eur. J. Med. Chem. 85 (2014) 487-497.
3. D.U. Ganihigama, S. Sureram, S. Sangher, P. Hongmanee, T. Aree, C. Mahidol, S. Ruchirawat, P. Kittakoop, Antimycobacterial activity of natural products and synthetic agents: pyrrolodiquinolines and vermelhotin as anti-tubercular leads against clinical multidrug resistant isolates of Mycobacterium tuberculosis, Eur. J. Med. Chem. 89 (2015) 1-12.
4. W.C. Song, W. Sangwook, H.P. Jung, K. Youngjoo, N. Younghwa, H.J. Lee,

Xanthone analogues as potent modulators of intestinal P-glycoprotein, Eur. J. Med. Chem. 93 (2015) 237-245.

5. C.G. Knight, T. Stephens, Xanthene-dye-labelled phosphatidylethanolamines as probes of interfacial pH. Studies in phospholipid vesicles, Biochem. J. 258 (1989) 683; (a) O. Sirkecioglu, N. Talinli, A. Akar, Chemical aspects of santalin as a histological stain, J. Chem. Res. (1995) 502.
6. (a) R.W. Lambert, J.A. Martin, J.H. Merrett, K.E.B. Parkes, G.J. Thomas, PCT Int. Appl. WO 9706178, Chem. Abstr. 126 (1997) 212377; (b) T. Hideo, Jpn. Tokkyo Koho JP 56005480, Chem. Abstr. 95 (1981) 80922;
7. S.M. Menchen, S.C. Benson, J.Y.L. Lam, W. Zhen, D. Sun, B.B. Rosenblum, S.H. Khan, M. Taing, US Patent, 6,583,168, Chem. Abstr. 139, US6583168 (2003) 54287.
8. D. Ashok, M.G. Devulapally, V.K. Aamate, S. Gundu, S. Adam, S.D.S. Murthy, S. Balasubramanian, B. Naveen, T. Parthasarathy, Novel pyrano [3,2-b]xanthen-7(2*H*)-ones: Synthesis, antimicrobial, antioxidant and molecular docking studies, Journal of Molecular Structure 1177 (2019) 215-228.
9. A.N. Dadhania, V.K. Patel, D.K. Raval, Ionic liquid promoted facile and green synthesis of 1,8-dioxo-octahydroxanthene derivatives under microwave irradiation, Journal of Saudi Chemical Society 21 (2017) 163-169.
10. A. Chavez, J. Cruz, A. Munoz, R.N. Yadav, D. Bandyopadhyay, B.K. Banik, Microwave-Induced Bismuth Iodide-Catalyzed Synthesis of Octahydroxanthenes, Heterocyclic Letters 7 (2017) 507-511.
    a. D. Ashok, R.S. Kumar, D.M. Gandhi, M. Sarasija, A. Jayashree, S. Adam, Solvent free microwave-assisted synthesis and biological evaluation of 2, 2-dimethylchroman-4-one based benzofurans, Heterocycl. Commun. 22 (2016) 363-368.
11. S.S. Zambre, S.N. Darandale, J.N. Sangshetti, D.B. Shinde, Microwave-assisted solvent-free one pot synthesis of isobenzofuran-1(3H)-ones using sulphamic acid catalyst, Arabian Journal of Chemistry 9 (2016) S1416–S1419.
12. B.A. Trofimov, A.V. Stepanov, A.G. Mal'kina, O.G. Volostnykh, O.A. Shemyakina, I.A. Ushakov, An Expedient Access into Functionalized Furan/3(2 H)-furanone Ensembles via Microwave-Assisted Domino Reactions, Synthetic Communications1 45 (2015) 2718–2729.
13. A. Detsi, M. Majdalani, C.A Kontogiorgis, D. Hadjipavlou-Litina, P. Kefalas, Natural and synthetic 2'-hydroxy-chalcones and aurones: Synthesis, characterization and evaluation of the antioxidant and soybean lipoxygenase inhibitory activity, Bioorg Med Chem 17 (2009) 8073–8085.
14. H.M. Sim, K.Y. Loh, W.K. Yeo, C.Y. Lee, M.L. Go, Aurones as Modulators of ABCG2 and ABCB1: Synthesis and Structure–Activity Relationships, Chem Med Chem 6 (2011) 713-724.
15. H. Cheng, L. Zhang, Y. Liu, S. Chen, H. Cheng, X. Lu, Z. Zheng, G.C. Zhou, Design, synthesis and discovery of 5-hydroxyaurone derivatives as growth inhibitors against HUVEC and some cancer cell lines, Eur J Med Chem 45 (2010) 5950–5957.
16. M. Roussaki, S.C. Lima, A.M. Kypreou, P. Kefalas, A.S.D Cordeiro, A. Detsi, Aurones: a promising heterocyclic scaffold for the development of potent antileishmanial agents, Int J Med Chem 2012 (2012) 196921.
17. D. Kerboeuf, M. Riou, F. Guégnard, Flavonoids and related compounds in parasitic disease control, Mini Rev Med Chem 8 (2008) 116–128.
18. A. Boumendjel, Aurones: a subclass of flavones with promising biological potential, Curr Med Chem 10 (2003) 2621–2630.

19. S. Shrestha, S. Natarajan, J.H. Park, D.Y. Lee, J.G. Cho, G.S. Kim, Y.J. Jeon, S.W. Yeon, D.C. Yang, N.I. Baek, Potential neuroprotective flavonoid-based inhibitors of CDK5/p25 from Rhus Parviflora, Bioorg Med Chem Lett 23 (2013) 5150–5154.
20. J. Schoepfer, H. Fretz, B. Chaudhuri, L. Muller, E. Seeber, L. Meijer, O. Lozach, E. Vangrevelinghe, P. Furet, Structure-based design and synthesis of 2-benzylidene-benzofuran-3-ones as Flavopiridol Mimics, J Med Chem 45 (2002) 1741–1747.
21. I.T. Kim, Y.M. Park, K.M. Shin, J.H. Ha, J.W. Choi, H.J. Jung, H.J. Park HJ, K.T. Lee, Anti-inflammatory and anti-nociceptive effects of the extract from Kalopanax pictus, Pueraria thunbergiana and Rhus verniciflua, J Ethnopharmacol 94 (2004) 165–173.
22. K.Y. Park, G.O. Jung, K.T. Lee, J.W. Choi, M.Y. Choi, G.T. Kim, H.J. Jung, H.J. Park, Antimutagenic activity of flavonoids from the heartwood of Rhus verniciflua, J Ethnopharmacol 90 (2004) 73–79.
23. M.J. Jung, H.Y. Chung, S.S. Kang, J.H. Choi, K.S. Bae, J.S. Choi, Antioxidant activity from the stem bark of Albizzia julibrissin, Arch Pharm Res 6 (2003) 458–462.
24. E.H. Lee, D.G. Song, J.Y. Lee, C.H. Pan, B.H. Um, S.H. Jung, Inhibitory effect of the compounds isolated from Rhus verniciflua on aldose reductase and advanced glycation endproducts, Biol Pharm Bull 31 (2008) 1626–1630.
25. M.Y. Song, G.S. Jeong, K.B. Kwon, S.O. Ka, H.Y. Jang, J.W. Park, Y.C. Kim, B.H. Park, Sulfuretin protects against cytokine-induced beta-cell damage and prevents streptozotocin-induced diabetes. Exp Mol Med 42 (2010) 628–638.
26. D. Ashok, K. Rangu, S. Gundu, A. Lakkadi, P. Tigulla, Microwave-assisted synthesis, molecular docking, and biological evaluation of 2-arylidene-2H-furo[2,3-f]chromen-3 (7H)-ones as antioxidant and antimicrobial agents, Med Chem Res 26 (2017) 1735–1746.
27. X. Hu, H. Lai, F. Zhao, S. Hu, Q. Sun, L. Fang, Microwave-Assisted Synthesis of Benzofuran-3(2H)-ones, Acta Chim. Slov. 66 (2019) 745–750.
28. A.B. Gawade, G.D. Yadav, Microwave assisted synthesis of 5-ethoxymethylfurfural in one pot from D-fructose by using deep eutectic solvent as catalyst under mild condition, Biomass and Bioenergy 117 (2018) 38–43.
29. A. Thakur, R. Singla, V. Jaitak, Coumarins as anticancer agents: a review on synthetic strategies, mechanism of action and SAR studies, Eur. J. Med. Chem. 101 (2015) 476-495.
30. A. Vogel, De l'existence de l'acide bezoïque dans la feve de tonka et dans les fleurs de melilot (On the existence of benzoic acid in the tonka bean and in the flowers of melilot), J. de Pharm. 6 (1820) 305-309.
31. W.H. Perkin, On the artificial production of coumarin and formation of its homologues, J. Chem. Soc. 21 (1868) 53-63.
32. M.E. Riveiro, N.D. Kimpe, A. Moglioni, R. Vazquez, F. Monczor, C. Shayo, C. Davio, Coumarins: old compounds with novel promising therapeutic perspectives, Curr. Med. Chem. 17 (2010) 1325-1338.
33. K.N. Venugopala, V. Rashmi, B. Odhav, Review on natural coumarin lead compounds for their pharmacological activity, Biomed. Res. Int. 2013 (2013) 1-14.
34. S. Emami, S. Dadashpour, Current developments of coumarin-based anticancer agents in medicinal chemistry, Eur. J. Med. Chem. 102 (2015) 611-630.
35. R.S. Keri, B.S. Sasidhar, B.M. Nagaraja, M.A. Santos, Recent progress in the drug development of coumarin derivatives as potent antituberculosis agents, Eur. J. Med. Chem. 100 (2015) 257-269.
36. M.M. Liu, X.Y. Chen, Y.Q. Huang, P. Feng, Y.L. Guo, G. Yang, Y. Chen, Hybrids of

phenylsulfonylfuroxan and coumarin as potent antitumor agents, J. Med. Chem. 57 (2014) 9343-9356.

37. A. Stefanachi, N. Hanke, L. Pisani, F. Leonetti, O. Nicolotti, M. Catto, S. Cellamare, R.W. Hartmann, A. Carotti, Discovery of new 7-substituted-4-imidazolylmethyl coumarins and 4'-substituted-2-imidazolyl acetophenones open analogues as potent and selective inhibitors of steroid-11beta-hydroxylase, Eur. J. Med. Chem. 89 (2015) 106-114.
38. D. Konrádová, H. Kozubíková, K. Doležal, J. Pospíšil, Microwave-Assisted Synthesis of Phenylpropanoids and Coumarins: Total Synthesis of Osthol, Eur. J. Org. Chem. 2017 (2017) 5204–5213.
39. A.R. Kaneria, R.R. Giri, V.G. Bhila, H.J. Prajapati, D.I. Brahmbhatt, Microwave assisted synthesis and biological activity of 3-aryl-furo[3,2-c]coumarins, Arabian Journal of Chemistry 10 (2017) S1100-S1104.
40. Y. Shi, B. Zhang, X.J. Chen, D.Q. Xu, Y.X. Wang, H.Y. Dong, S.R. Ma, R.H. Sun, Y.P. Hui, Z.C. Li, Osthole protects lipopolysaccharide-induced acute lung injury in mice by preventing down-regulation of angiotensin-converting enzyme 2, Eur. J. Pharm. Sci. 48 (2013) 819-824.
41. H.J. Liang, F.M. Suk, C.K. Wang, L.F. Hung, D.Z. Liu, N.Q. Chen, Y.C. Chen, C.C. Chang, Y.C. Liang, Osthole, a potential antidiabetic agent, alleviates hyperglycemia in db/db mice, Chem. Biol. Interact. 181 (2009) 309-315.
42. L. Wu, X. Huang, J. Li, R. Zhang, H. Hu, Recent advances in the multifunction of a natural occurring coumarin: osthole, J. Intercult. Ethnopharmacol. 2 (2013) 57-66.
43. Y.W. Liu, Y.T. Chiu, S.L. Fu, Y.T. Huang, Osthole ameliorates hepatic fibrosis and inhibits hepatic stellate cell activation, J. Biomed. Sci. 22 (2015) 63.
44. S. Vogl, M. Zehl, P. Picker, E. Urban, C. Wawrosch, G. Reznicek, J. Saukel, B. Kopp, Identification and quantification of coumarins in Peucedanum ostruthium (L.) Koch by HPLC-DAD and HPLC-DAD-MS, J Agric Food Chem 59 (2011) 4371-4377.
45. Y. Wei, T. Zhang, Y. Ito, Preparative isolation of osthol and xanthotoxol from Common Cnidium Fruit (Chinese traditional herb) using stepwise elution by high-speed counter-current chromatography, J Chromatogr. A. 1033 (2004) 373-377.
46. X. Cao, Y. Xu, Y. Cao, R. Wang, R. Zhou, W. Chu, Y. Yang, Design, synthesis, and structure-activity relationship studies of novel thienopyrrolidone derivatives with strong antifungal activity against Aspergillus fumigates, Eur J Med Chem 102 (2015) 471-476.
47. A.K. Bhattacharya, H.R. Chand, J. John, M.V. Deshpande, Clerodane type diterpene as a novel antifungal agent from Polyalthia longifolia var. pendula, Eur J Med Chem 94 (2015) 1-7.
48. A.R. Villalva, D. Gonzalez-Calderon, C. Gonzalez-Romero, M. Morales-Rodríguez, B. Jauregui-Rodríguez, E. Cuevas-Yanez, A facile synthesis of novel miconazole analogues and the evaluation of their antifungal activity, Eur J Med Chem 97 (2015) 275-279.
49. M.Z Zhang, R.R. Zhang, J.Q. Wang, X. Yu, Y.L. Zhang, Q.Q. Wang, W.H. Zhang, Microwave-assisted synthesis and antifungal activity of novel fused Osthole derivatives, Eur J Med Chem 124 (2016) 10-16.
50. R.R. Zhang, J. Liu, Y. Zhang, M.Q. Hou, M.Z. Zhang, F. Zhou, W.H. Zhang, Microwave-assisted synthesis and antifungal activity of novel coumarin derivatives: Pyrano[3,2-c]chromene-2,5-diones, Eur J Med Chem 116 (2016) 76-83.
51. K. Ostrowska, E. Hejchman, D. Maciejewska, A. Włodarczyk, K. Wojnicki, D.

Matosiuk, A. Czajkowska, I. Młynarczuk-Biały, Ł. Dobrzycki, Microwave-assisted preparation, structural characterization, lipophilicity, and anti-cancer assay of some hydroxycoumarin derivatives, Monatsh Chem 146 (2015) 89–98.

52. D. Ashok, B.V. Lakshmi, S. Ravi, A. Ganesh, Microwave-assisted synthesis of substituted 4-chloro-8-methyl-2-phenyl-1,5-dioxa-2H-phenanthren-6-ones and their antimicrobial activity, Med Chem Res 24 (2015) 1487–1495.
53. I.T.L. Ramos, T.M.S. Silva, C.A. Camara, Synthesis of new 6- and 8-Alkenyl-3,7,3',4'-Tetramethoxyquercetin derivatives by microwave-assisted Heck coupling, Synthetic Communications 49 (2019) 2583–2589.
54. M.D. McReynolds, J.M. Dougherty, P.R. Hanson, Synthesis of Phosphorus and Sulfur Heterocycles via Ring-Closing Olefin Metathesis, Chem Rev. 104 (2004) 2239-2258.
55. T. Nash, W.G. Rice, Efficacies of Zinc-Finger-Active Drugs against Giardia lamblia, Antimicrob. Agents Chemother. 42 (1998) 1488-1492.
56. N.B. Perry, J.W. Blunt, M.H.G. Munro, Cytotoxic pigments from new zealand sponges of the genus latrunculia : discorhabdins a, b and c, Tetrahedron 44 (1988) 1727-1734.
57. M.R. Khan, S. Zaib, M.K. Rauf, M. Ebihara, A. Badshah, M. Zahid, M.A. Nadeem, J. Iqbal, Solution-phase microwave assisted parallel synthesis, biological evaluation and in silico docking studies of 2-chlorobenzoyl thioureas derivatives, Journal of Molecular Structure 1164 (2018) 354-362.
58. S. Li, X. Chen, J. Xu, Microwave-assisted copper-catalyzed stereoselective ring expansion of three-membered heterocycles with a-diazo-b-dicarbonyl compounds, Tetrahedron 74 (2018) 1613-1620.
59. A.K. Singh, S. Thakur, B. Pani, B. Chugh, H. Lgaz, I.-M. Chung, P. Chaubey, A.K. Pandey, J. Singh, Solvent-freemicrowave assisted synthesis and corrosion inhibition study of a series of hydrazones derived from thiophene derivatives: Experimental, surface and theoretical study, Journal of Molecular Liquids 283 (2019) 788–803.
60. Ch. Anjaiah, M. Nagamani, Ch. Abraham Lincoln, D. Ashoka, Microwave-Assisted Synthesis and Antimicrobial Activity of 3-(Arylsulfanyl)-4-hydroxy-2H-chromen-2-ones1, Russian Journal of General Chemistry 88 (2018) 2149–2153.
61. Ch. Anjaiah, M. Nagamani, Ch. Abraham Lincoln, D. Ashok, Microwave Assisted Synthesis of 1-(Arylthio)naphthalen-2-ols and Their Antimicrobial Activity1, Russian Journal of General Chemistry 87 (2017) 2930–2932.
62. R.H. Fałdyga, P. Grzelak, P. Pipiak, G. Mlostoń, Microwave assisted synthesis of ferrocenyl and hetaryl functionalized thioketones, PHOSPHORUS, SULFUR, AND SILICON 192 (2017) 197-198.
63. A.S. Kermani, Microwave-assisted one-pot synthesis of 2-nitroalkylidene-1,3-oxathiolane derivatives, Journal of Sulfur Chemistry 37 (2016) 105–113.
64. G. Mlostoń, R.H. Fałdyga, M. Jeske, M. Godziszewska, K. Urbaniak, H. Heimgartner, Microwave-assisted reactions of α-diazoketones with hetaryl and ferrocenyl thioketones, Journal of Sulfur Chemistry 39 (2018) 47–63.
65. R. Lisiak, J. Mochowski, Facile Method for Conversion of 2-(Chloroseleno)benzoyl Chloride into 2-Substituted 3-Hydroxybenzo[b]selenophenes, Synth. Commun. 39 (2009) 4271-4281.
66. M. K. Staples, R. L. Grange, J. A. Angus, J. Ziogas, N. P. H. Tan, M. K. Taylor, C. H. Schiesser, Tandem free-radical addition/substitution chemistry and its application to the preparation of novel AT1 receptor antagonists, Org. Biomol. Chem. 9 (2011) 473-479.
67. K. Takimiya, Y. Kunugi, Y. Konda, H. Ebata, Y. Toyoshima, 2,7-

Diphenyl[1]benzoselenopheno[3,2-b][1]benzoselenophene as a Stable Organic Semiconductor for a High-Performance Field-Effect Transistor, T. Otsubo, J. Am. Chem. Soc. 128 (2006) 3044-3050;

68. H. Ebata, E. Miyazaki, T. Yamamoto, K. Takimiya, Synthesis, Properties, and Structures of Benzo[1,2-b:4,5-b‘]bis[b]benzothiophene and Benzo[1,2-b:4,5-b‘]bis[b]benzoselenophene, Org. Lett. 9 (2007) 4499-4502.
69. T. Yamamoto, K. Takimiya, Facile Synthesis of Highly π-Extended Heteroarenes, Dinaphtho[2,3-b:2‘,3‘-f]chalcogenopheno[3,2-b]chalcogenophenes, and Their Application to Field-Effect Transistors, J. Am. Chem. Soc. 29 (2007) 2224-2225.
70. P. Arsenyan, E. Paegle, S. Belyakov, Microwave-assisted cyanation of 3-bromo-3-(1-hydroxyalkyl)benzo[b]selenophene derivatives, Mendeleev Commun. 25 (2015) 119–120.
71. R. N. Yadav, L. Salazar, A.K. Singh, B.K. Banik, Microwave-Induced Bismuth Nitrate Impregnated Clay-Mediated Novel Nitration of 9,19-Dihydrophenanthrene: A Precursor for New Heterocycles, Heterocyclic Letters 8 (2018) 273-276.
72. R. Henyecz, Microwave-assisted synthesis of phosphonic and phosphinic esters and phosphine oxides by the Hirao reaction, Phosphorus, Sulfur, and Silicon and the Related Elements 194 (2019) 372–376.
73. G.S. Ananthnag, J.T. Mague, M.S. Balakrishna, A Cyclodiphosphazane Based Pincer Ligand, [2,6-{l-(tBuN)$_2$P (tBuHN)PO}2C$_6$H$_3$I]: Ni^{II}, Pd^{II}, Pt^{II} and Cu^{I} Complexes and Catalytic Studies, Dalton Trans. 44 (2015) 3785–3793.
74. G. Keglevich, R. Henyecz, Z. Mucsi, N.Z. Kiss, The Palladium Acetate-Catalyzed Microwave-Assisted Hirao Reaction without an Added Phosphorus Ligand as a “Green” Protocol: A Quantum Chemical Study on the Mechanism, Adv. Synth. Catal. 359 (2017) 4322–4331.
75. E. Jablonkai, G. Keglevich, Catalyst-Free P–C Coupling Reactions of Halobenzoic Acids and Secondary Phosphine Oxides under Microwave Irradiation in Water, Tetrahedron Lett. 56 (2015) 1638–1640.
76. Ł. Janczewski, A. Gajda, J. Braszczyńska, T. Gajda, Microwave-assisted synthesis of dialkyl ω-azidoalkylphosphonates, Synthetic Communications 46 (2016) 1625–1633.
77. A. Abdulwadood, A.S.H. Alsamarrai, Microwave assisted base-catalyzed 1,3-isomerization of 7-substituted cycloheptatriene bearing electron withdrawing groups, Journal of King Saud University – Science 32 (2020) 332–336.
78. T.-C. Chang, S.J. Yu, Microwave-Assisted Catalytic Acetylation of Alcohols by Gold-Nanoparticle–Supported Gadolinium Complex, Synthetic Communications 45 (2015) 651-662.
79. Ł. Janczewski, M. Walczak, J. Frączyk, Z.J. Kamiński, B. Kolesińska, Microwave-assisted Cannizzaro reaction—Optimisation of reaction conditions, Synthetic Communications 49 (2019) 3290–3300.
80. A. Rayar, M.S.-I. Veitía, C. Ferroud, An efficient and selective microwave-assisted Claisen-Schmidt reaction for the synthesis of functionalized benzalacetones, SpringerPlus 4 (2015) 221.
81. A. Mhanna, L. Chupin, C.H. Brachais, D. Chaumont, G. Boni, L. Brachais, J.P. Couvercelle, L. Lecamp, L. Plasseraud, Efficient microwave-assisted synthesis of glycerol monodecanoate, Eur. J. Lipid Sci. Technol. 120 (2018) 1700133.
82. M.A. Ibrahim, Microwave-assisted synthesis of a-aryl malonates: Key intermediates for the preparation of azaheterocycles, Arabian Journal of Chemistry 9 (2016) S1973–S1983.

Received on February 27, 2024.

Aparna Das obtained her Ph. D. degree in Material science/nanophysics from Joseph Fourier University at French Alternative Energies and Atomic Energy Commission (CEA), France. Her postdoctoral experiences include working as a research scientist at the California Nano Systems Institute and Electric Engineering Department and as an experienced researcher at the Nanowiring-Marie Curie Initial Training Network, Georg August Universität Göttingen, Germany. Currently, she is working as an Assistant Professor at Prince Mohammad Bin Fahd University, Saudi Arabia.

Dr. Das's research interests include Computer-assisted Physico-chemical methods, quantum mechanical calculations, interdisciplinary science (Biology, Chemistry, and Physics) for drug development, computer-aided drug design, microwave applications, photochemical reactions, III-Nitride based chemical sensors, solar cells, optoelectronic devices, synthesis of thin layers and nanostructures including Quantum wells, quantum dots and nanowires. Dr. Das has also experience in Molecular-beam epitaxy (MBE), Plasma-enhanced chemical vapor deposition (PECVD), sputtering, Atomic Force Microscopy (AFM), Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD) and Spectroscopy, UV and IR photoluminescence, transmission spectroscopy, time-resolved photoluminescence, Raman Spectroscopy, Hall Effect measurements, Spin coating, Reactive-ion etching (RIE), Electron beam evaporator, Rapid thermal processing (RTP), Electron-beam lithography, Photolithography, Wire bonding, Profilometer and Wafer saw, Optical Fibers (cleaving, cutting, splicing, launching light, loss measurements and characterization of various parameters), and in the operation of various Lasers, light emitting diodes (LEDs), spectrophotometers, fluorometers, interferometers and photomultiplier tubes.

Dr. Das is the author of a book and she has written several book chapters published by internationally reputed publishers. She has published many papers. Dr. Das has served as a guest editor of two international journals and she has acted as a reviewer. Dr. Das has obtained competitive grants. She has received young women researcher award, European microscopy society (EMS) outstanding paper awards and several international fellowships such as Marie-Curie fellowship, CEA-CNRS research fellowship and Brain Korea 21 fellowship.

Bimal Krishna Banik conducted postdoctoral research at Case Western Reserve University and Stevens Institute of Technology. Dr. Banik was a Tenured Full Professor in Chemistry and First President's Endowed Professor in Science & Engineering at the University of Texas-Pan American. He served as the Vice President of Research & Education Development of the Community Health System of Texas. At present, Dr. Banik is a Full Professor of the Deanship of Research Development & College of Natural Sciences & Human Studies at the Prince Mohammed Bin Fahd University in Kingdom of Saudi Arabia.

Professor Banik taught organic and medicinal chemistry to B. S., M. S., and Ph. D. students in USA and Saudi Arabia universities. He mentored approximately 300 students and teachers, 20 postdoctoral fellows, and 7 Ph. D. research scientists and advised 26 university/college faculties. Dr. Banik acted as the advisor of two students' organizations that has 1400 students.

Professor Banik conducted synthetic chemistry and chemical biology research on cancers, antibiotics, hormones, catalysis and microwave-induced reactions. As the Principal Investigator, he was awarded $7.25 million in grants from NIH, NCI and Private Foundations. Importantly, he has 580 peer-reviewed publications along with 513 presentation abstracts. He is a reviewer of 93, editorial board member of 28, editor-in-chief of 16, founder of 9, associate editor of 4 and guest editor of 10 journals.

Professor Banik received the Indian Chemical Society's Life-Time Achievement Award; Mahatma Gandhi Pravasi Honor Gold Medal from the UK Parliament; ICS's Professor P. K. Bose Endowment Medal; Dr. M. N. Ghosh Gold Medal; University of Texas Board of Regents' Outstanding Teaching award; ACS Member Service award; NCI webpage recognition; Best Researcher and Mentor Awards by the UTPA; Burdwan University Eminent Alumnus recognition; Professor Banik is also recognized as a "Distinguished Researcher" and a "Distinguished Scientist" by Scientific Organizations.