COMPUTATIONAL INVESTIGATIONS ON THE STRUCTURE AND REACTIVITY OF QUATERNARY AMMONIUM TRIBROMIDES

by

RITUPARNA KARMAKER

Submitted to

NAGALAND UNIVERSITY

In Partial Fulfilment of the Requirements for Award of the Degree

of

DOCTOR OF PHILOSOPHY IN CHEMISTRY

DEPARTMENT OF CHEMISTRY
NAGALAND UNIVERSITY
LUMAMI-798627
NAGALAND, INDIA

2022

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Department of Chemistry

DECLARATION

I, **Miss Rituparna Karmaker** bearing Ph.D. Registration No.**792/2017** with effect from **30th August 2016**, hereby declare that the subject matter of my Ph. D. thesis entitled **“Computational Investigations on the Structure and Reactivity of Quaternary Ammonium Tribromides”** is the record of work done by me, and that the contents of this thesis did not form the basis for award of any previous degree to me or to anybody else known to the best of my knowledge. This thesis has not been submitted by me for any other Research Degree in any other University/Institute.

This Ph. D. thesis is submitted in compliance with the UGC Regulation 2016 dated May 05, 2016 (Minimum Standard and Procedure for Award of M. Phil. /Ph. D. Degree) to the Nagaland University for the degree of Philosophy in chemistry.

(Rituparna Karmaker)

(Upasana Bora Sinha)
Head
Department of Chemistry
Nagaland University

(Upasana Bora Sinha)
Supervisor

NAGALAND UNIVERSITY

(A Central University Estd. By the Act of Parliament No. 35 of 1989)
Headquarters : Lumami – 798627,Nagaland, India

Professor Upasana Bora Sinha
Department of Chemistry

e-mail: upasana@nagalanduniversity.ac.in
upasanaborasinha@gmail.com

CERTIFICATE

This is to certify that **Miss Rituparna Karmaker,** a registered Research Scholar for Ph. D. degree in Chemistry under Nagaland University has carried out his research work under my guidance. His thesis entitled **“Computational Investigations on the Structure and Reactivity of Quaternary Ammonium Tribromides”** embodies the original research work and has fulfilled all the requirements according to the rules of this University regarding the investigations.

Further, to the best of my knowledge, the research work has not been submitted to any University for the award of any degree or diploma to any University/Institution.

(Upasana Bora Sinha)
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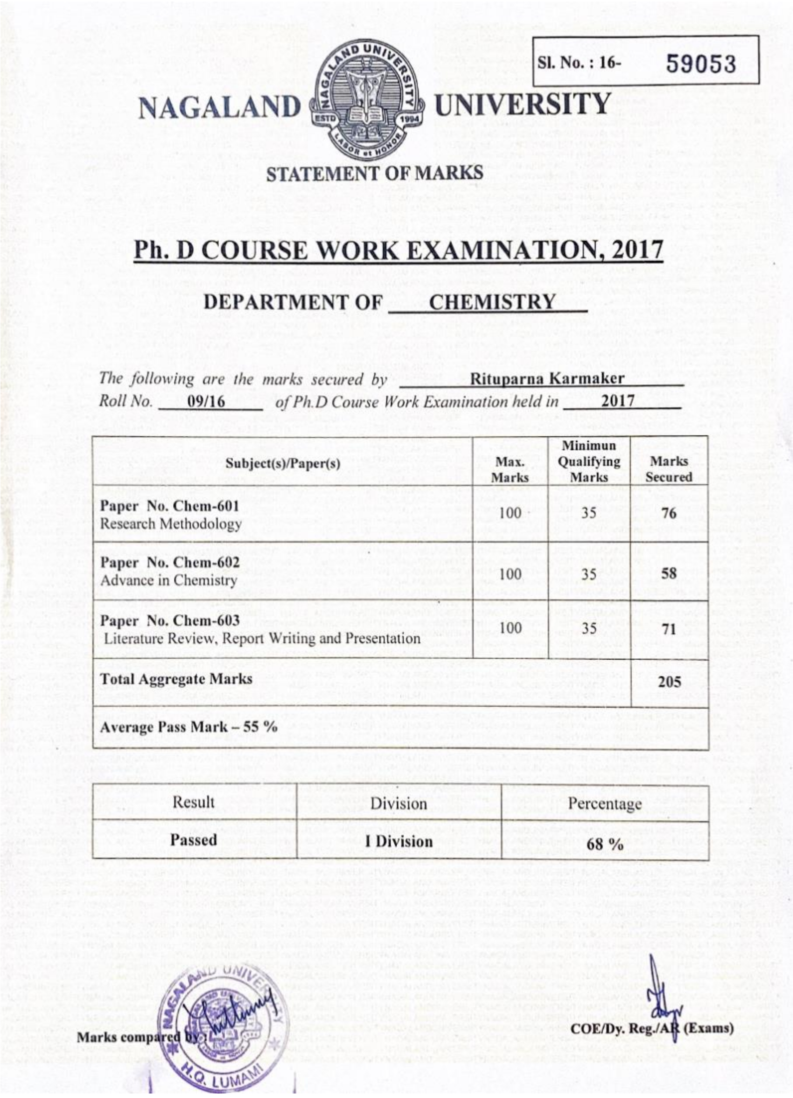

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STATEMENT OF MARKS

Ph. D COURSE WORK EXAMINATION, 2017

DEPARTMENT OF CHEMISTRY

The following are the marks secured by **Rituparna Karmaker**
Roll No. **09/16** *of Ph.D Course Work Examination held in* **2017**

Subject(s)/Paper(s)	Max. Marks	Minimun Qualifying Marks	Marks Secured
Paper No. Chem-601 Research Methodology	100	35	**76**
Paper No. Chem-602 Advance in Chemistry	100	35	**58**
Paper No. Chem-603 Literature Review, Report Writing and Presentation	100	35	**71**
Total Aggregate Marks			**205**
Average Pass Mark – 55 %			

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Passed	**I Division**	**68 %**

Marks compared by

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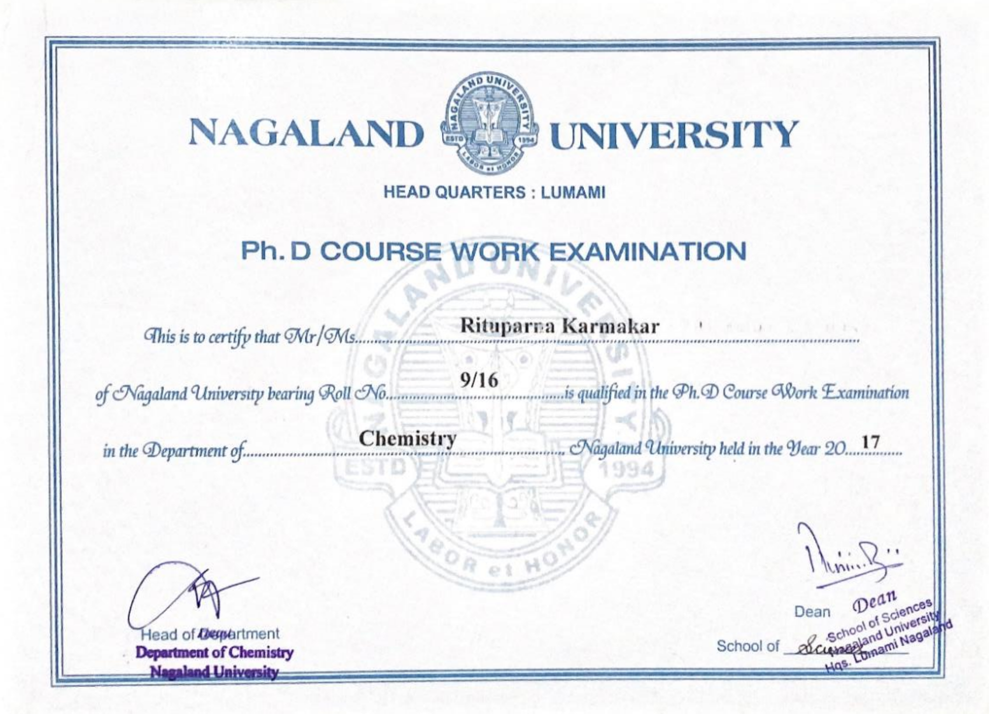

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Ph. D COURSE WORK EXAMINATION

This is to certify that Mr/Ms. **Rituparna Karmakar**
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in the Department of **Chemistry** *, Nagaland University held in the Year 20***17**

Head of Department
Department of Chemistry
Nagaland University

Dean
Dean
School of Sciences
Nagaland University
Hqs. Lumami Nagaland

School of

ACKNOWLEDGMENT

At the very outset, with a deepest sense of gratitude, I wish to express my sincere thanks to my supervisor, Prof. Upasana Bora Sinha for her proficient guidance, encouragement, inspiration, and creative and scientific ideas which helped me to enhance my knowledge and have inspired me to take right decisions at crucial moments. I am also thankful to her for giving me freedom to pursue my own interests and I find myself privileged to have worked under her kind guidance.

It is my pleasure to extend my heartfelt gratitude to Prof. Dipak Sinha, Department of Chemistry, Nagaland University, who has always encouraged me cultivate scientific thoughts and decisive insights.

I would like to acknowledge my sincere gratitude to all the faculty members, Prof. M. Indira Devi, Dr. I. Tovishe Phucho, Dr. M. Prabhakar, Dr. Nurul Alam Choudhury, and Dr. Seram Dushila Devi for their extended help and inspiration all through my research period.

It is my immense pleasure to express my thanks to Prof. Nikhil Guchhait, Calcutta University, who gave me a wonderful opportunity to work in their research group for a couple of months and provided me with computational facility and training.

I wish to acknowledge my sincere gratitude to Dr. Aniruddha Ganguly, Scottish Church College, Kolkata, for his teachings on the Gaussian software.

I wish to acknowledge my sincere gratitude to Nagaland University, Lumami for all the facilities that were made available to me.

Further, I extend my gratitude to DST-INPIRE fellowship for the financial assistance to carry my thesis work smoothly.

I am extremely grateful to Mr. Bendangtemsu, Ms. Temsuinla Amer, Ms Sunepjungla, and Ms Lovi for their immense support during my research period.

I owe my sincere gratitude all my labmates, Dr. Kikoleho Richa, Ms. Naruti Longkumer, Mr. Apuchu R. Sangtam, Mr. Basanta Singha, Mrs. Angunuo Khieya, Ms. Narola Imchen, Ms. Penlisola Longkumer, and Mr. Partha Pratim Gogoi for their love and support.

I also take this opportunity to thank all the other research scholars from different labs and departments for their wonderful friendship and encouragement.

Finally, my Ph. D. endeavor could not have been completed without the endless love, unending support, tolerance and blessings from my family. I wish to express my sincere gratitude to my mother and my brother.

(Rituparna Karmaker)

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Glossary

Term	**Definition**
Computational chemistry	The branch of chemistry where computational calculations are employed for solving certain complex chemical problems
Computational cost	The time required for completion of any computational calculation is called its computational cost which is measured in terms of time
Quantum mechanics	Explanation of the motion and interaction of atoms and sub-atomic particles using mathematical equations
Schrodinger’s equation	It is a mathematical equation which is used to determine the position and energy of an electron in space and time by considering the wave function of the electron
Wave function	It is a mathematical term which relates with the position of electrons
Quantum Hamiltonian	It is an operator with respect to the total energy of a system
Electronic level	Understanding chemical structures from studying the electron distribution in the system
Hypervalent	A molecule which has one or more main group elements bearing more than eight electrons in their valence shells

Modelling compounds	Designing new compounds or modifying existing compounds
Structural geometry	The arrangement of atoms in a compound
Symmetrical structure	One half is the mirror image of the other half
Geometry optimization	It is the process of energy minimization by arranging the atoms of a compound in such a way that the repulsion between them is minimum
Optimized structure	The structure obtained after geometry optimization
Input file	The initial structure of any compound before optimization
Output file	The final structure of any compound after optimization
Level of theory	The quantum mechanical method and the basis set used for a certain calculation in Gaussian or any other structure simulation software together is called the level of theory
Electronic parameters/molecular descriptors/reactivity descriptors	The parameters obtained by computational calculations which describe the properties of any compound
Potential energy surface	It defines the potential energy of atoms in a system, with respect to certain parameters, usually the position of each atom
Stationary points	The maxima and minima of a graph are called stationary points (maxima and minima represent energy)

Imaginary frequency	Negative frequency
Dielectric constant	It is the measure of the capacity of a substance to store electrical energy
Green chemistry	It is branch of chemistry which aims on reducing or eliminating the use or production of hazardous substances by means of developing environmentally benign substances and processes
Greenness-efficiency correlation of solvents	Relation between the greenness and efficiency of solvents

List of abbreviations

Abbreviation	**Meaning**
AC	Activated carbon
BAC	Brominated activated carbon
Br_2	Bromine molecule
Br_3^-	Tribromide anion/ Tribromide ion
B3LYP	Becke 3-Parameter (Exchange), Lee, Yang and Parr
CCl_4	Carbon tetrachloride
CTMATB	Cetyltrimethyl ammonium tribromide
$CTMA^+$	Cetyltrimethyl ammonium cation
DFT	Density functional theory
DMSO	Dimethyl sulfoxide
GSK	GlaxoSmithKline
HOMO	Highest occupied molecular orbital
IM	Intermediate
IRC	Intrinsic reaction path
LUMO	Lowest unoccupied molecular orbital
MK	Merz-Singh-Kollman
NBO	Natural bond orbital

OAC	Oxygen functionals containing activated carbon
OBAC	Oxygen functionals containing brominated activated carbon
PCM	Polarizable continuum model
QATB	Quaternary ammonium tribromide
QA^+	Quaternary ammonium cation
RM	Reaction mixture
TBAB	Tetrabutyl ammonium bromide
TBATB	Tetrabutyl ammonium tribromide
TBA^+	Tetrabutyl ammonium cation
t-BuOH	Tert-Butyl alcohol
TEATB	Tetraethyl ammonium tribromide
TPATB	Tetrapropyl ammonium tribromide
TLC	Thin layer chromatography
TS	Transition state
XAS	X-ray absorption spectroscopy
XPS	X-ray photoelectron spectroscopy
XRD	X-ray diffraction

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Chapter 1

Introduction

With the advancement of science, the need to understand chemical processes at an electronic level has become vital for obtaining comprehensive information about the same. In fact, in recent times, it has become a desired need to develop a theoretical background of any chemical compound and/or reaction methodology first before proceeding to wet lab experiments with the excellent aim of avoiding hazards and wastage of chemicals. And for this purpose, computational chemistry plays an important role in understanding chemicals/reactions at an electronic level, since it is impossible to calculate electronic data manually beyond the hydrogen atom. There are a number of advantages in opting for computational calculations first, which will be discussed thoroughly in this thesis. As a matter of fact, certain theoretical calculations on their own can clarify a lot of queries and prove numerous facts if and when assessed employing appropriate computational methods. Therefore, in this thesis, an attempt has been made to develop a theoretical background of a popular class of brominating agents, QATBs, using computational techniques. The details of the study are explained conclusively in the upcoming parts of this thesis.

1.1. Quaternary ammonium tribromides

1.1.1. Introduction to QATBs

Quaternary ammonium tribromides (QATBs) are a series of ionic compounds with a cationic moiety (QA^+) and a tribromide anion (Br_3^-). Where the cationic moiety consists of a nitrogen atom attached to four alkyl and/or aryl groups and is ionically bonded to the tribromide ion. In the tribromide ion, a negative charge is spread over three bromine atoms[1]. Over the years, different types of QATBs have been synthesized and applied for different types of reactions. QATBs are most popular for their efficiency in bromination reactions of different kinds of substrates and also for certain oxidation reactions[2–8].

1.1.2. Types of QATBs

In literature, many organic tribromides have been reported (Figure 1.1), that include tetramethylammonium tribromide (TMATB)[9], tetrabutylammonium tribromide (TBATB)[7], tetraethylammonium tribromide (TEATB)[10], cetyltrimethylammonium tribromide (CTMATB)[11], phenyltrimethylammonium tribromide (PTATB)[12,13], benzyl trimethylammonium tribromide (BTMATB)[14,15], pyridine hydrobromide perbromide (PHPB)[16,17], pentylpyridinium tribromide (PPTB)[18], 1-benzyl-4-aza-1-azonia-bicyclo [2.2.2] octane tribromide (DABCO tribromide)[19,20], 1,8-diazabicyclo [5.4.0]-undec-7-ene hydrobromide perbromide ($DBUHBr_3$)[21,22], and 1-butyl-3-methylimidazoliumtribromide (bmimTB)[23,24], 1,2-dipyridiniumditribromide-ethane (DPTBE)[25,26], etc.

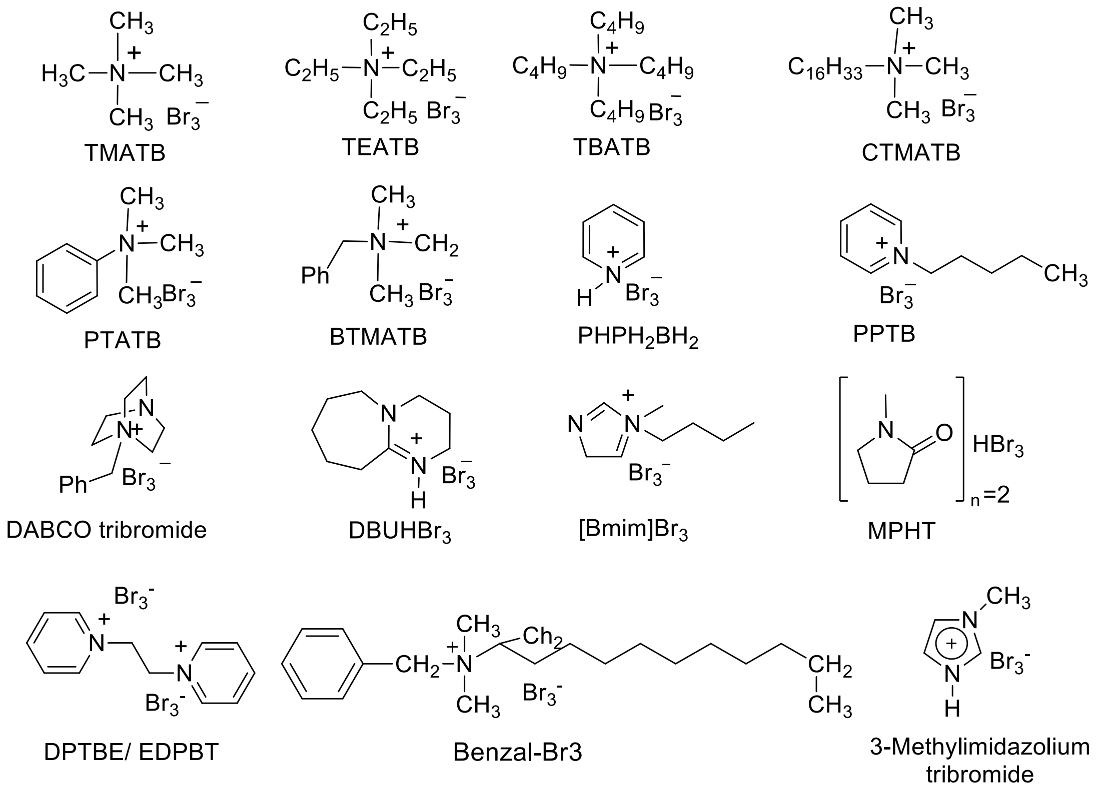


Figure 1.1. Some common QATBs

1.1.3. Other tribromides

Considering the popularity of ammonium tribromides, over the years different types of tribromides have been synthesized, such as phosphonium tribromides, lanthanide tribromides, etc[3,27–29]. For example, Mhamdi *et al.*, 2021, reported the solvent effect and annealing treatment on the properties of Methylammonium lead tribromide thin films[30]. Koutsu *et al.*, 2021, reported the synthesis of Tetrabutylphosphonium tribromide (figure 1.2) and further reported its phase transfer properties in organic transformations[31]. Again, Abia *et al.*, 2021, reported the crystal structure and thermal evolution of formamidinium lead tribromide, $CH(NH_2)_2PbBr_3$[32]. Zhao *et al.*, 2022, reported 1,3,5-Tris(4-cyanopyridinium-1-ylmethyl)-benzene tribromide as the base for covalent triazine frameworks in order to capture and convert CO_2[33]. Noorozi-Shad *et al.*, 2022, reported the synthesis of Propane-3–bromo-1-(triphenyl phosphonium) tribromide (figure 1.3) and thereby showing the bromination of alkenes and aromatic using the synthesized reagent as the brominating agent[34].

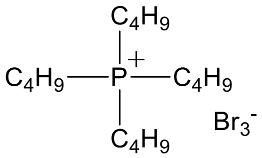


Figure 1.2. TBPTB

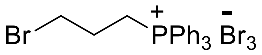


Figure 1.3. Propane-3–bromo-1- (triphenyl phosphonium) tribromide

An extensive literature survey revealed that in addition to the above stated monomeric tribromides, there are a number of polymeric tribromides which have been synthesized and applied for different types of applications. Hossein *et al.*, 2010, prepared Poly(diallyldimethylammonium tribromide) (figure 1.4.1) and used as a brominating agent for α-bromoacetalization of ketones, bromination of alkenes and regioselective bromination of activated aromatic compounds[35]. Verma *et al.*, 2011, developed Poly(ethylene glycol) Embedded Potassium Tribromide (PEG.KBr$_3$, figure 1.4.2) and used as a recyclable catalyst for oxidation of alcohols[36]. Han *et al.*, 2019, prepared Poly(vinylbenzyltrimethylammonium tribromide) resin (PVBMATB resin, figure 1.4.3) and employed for α-bromination and α-bromoacetalization of acetophenones[37]. Again, Zheng *et al.*, 2020, reported PVBMATB resin as an Efficient Polymeric Catalyst in the Acetalization and Diacetylation of Benzaldehydes[38].

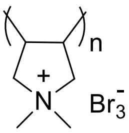


Figure 1.4.1. Poly(diallyldimethylammonium tribromide)

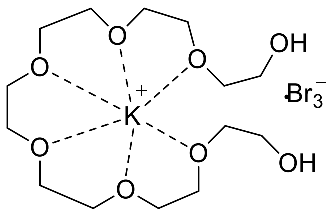


Figure 1.4.2. PEG.KBr3[36]

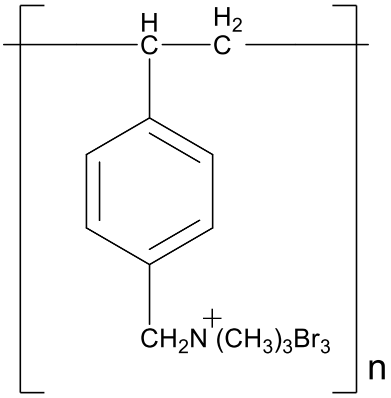


Figure 1.4.3. PVBMATB resin[37]

1.1.4. Structure of other trihalides

Based on literature reports it is understood that in case of I_3^-, the structure is slightly distorted from linearity and the central iodine is non-equidistant from the terminal iodine atoms[39,40].

Pimental, 1950[39], studied the bonding in trihalide ions, where the structural geometry of triiodide was also mentioned. He stated that the trihalide ions are found to be linear. The triiodide ion may slightly deviate from linearity by a few degrees, and the central iodine atom seems to be non-equidistant from the end iodine atoms. The trihalide bonds are apparently slightly longer and presumably slightly weaker than the corresponding halogen bonds. Thereafter, Wiebenga *et al.*, 1961[40], attempted to understand the structures of certain interhalogen compounds and polyhalides where they also studied the structural geometry of trihalides using XRD, emphasizing specifically on triiodide as shown in the figure 1.5 and 1.6 below.

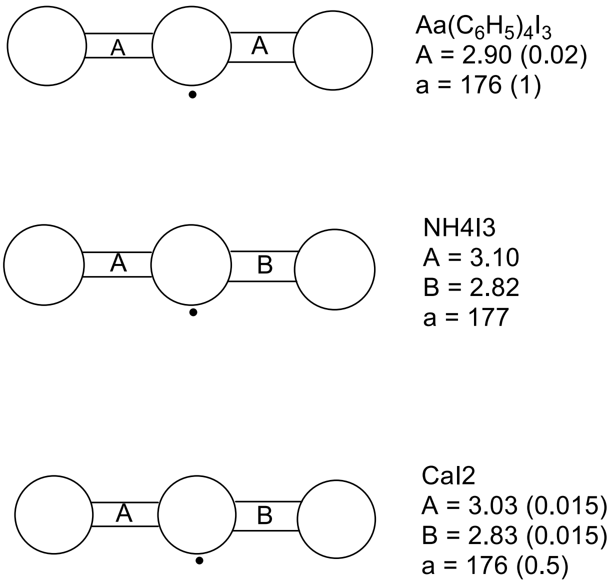


Figure 1.5. Structure of triiodide ions[40]

The structures observed for the triiodide ion are interesting in that symmetrical as well as asymmetrical triiodide ions have been found to exist in the solid triiodides. Wiebenga *et al.*, 1961, further stated that in the trihalide ions a linear symmetrical model is obtained when the three lone pairs occupy the equatorial orbitals, in which their mutual repulsion is probably at a minimum, and the bond pairs go into the remaining orbitals. Deviation from a symmetrical structure, such as is observed in the triiodide ions in many cases, must in this picture be due to secondary causes, probably to the influence of the environment in the crystal[40].

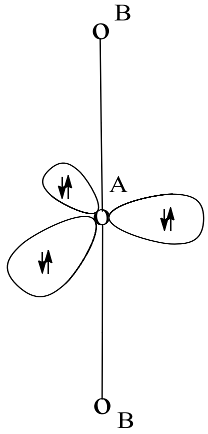


Figure 1.6. Disposition of bonds and lone pairs when sp^{3}d hybridization is assumed in trihalide ions[40].

1.1.5. Nature of bonding in other trihalides

The nature of bonding in any compound is a vital component which aids in understanding various features of the compound like its chemical and physical properties. However, the type of bonding in trihalides has not been explained univocally. The role of the tribromide ion (Br_3^-) in diverse organic transformations has been well studied and documented for decades now[2,41]. While it is known that this ion forms through the reaction of bromide with bromine[39], similar to other polyhalide ions such as I_3^-, with the central atom being hypervalent, the chemical nature of bonding in the tribromide moiety has been somewhat of an ambiguity. Polyhalide ions are formed when halides react with halogens or interhalogens, as exemplified through the formation of a trihalide ions such as $As(C_6H_5)_4I_3$, NH_4I_3, CsI_3 etc., with the central atom being hypervalent[40]. The chemical nature of bonding in such molecules has been somewhat of an ambiguity so far as it deviates from the general octet rule and thus cannot be explained with the help of valence bond theory[42,43]. Many researchers have attempted earlier to explain the stability by valence bond method considering the participation of d-orbitals on the central ion, however it proved to be futile. An alternative explanation was proposed by Pimentel and Rundle five decades ago on the basis of molecular orbitals and considering a delocalized three center σ-bonding (one bonding, one non-bonding and one anti-bonding molecular orbital (figure.1.7.(a)) to determine the stability of trihalides[39,44]. Thereafter different reports have discussed that in trihalide, there are four electrons, two of which occupy the bonding molecular orbital and the other two electrons occupy the non- bonding molecular orbitals give one bond spread over two positions (bond order of 0.5) which explains the nature of the stability of the long bonds[45].

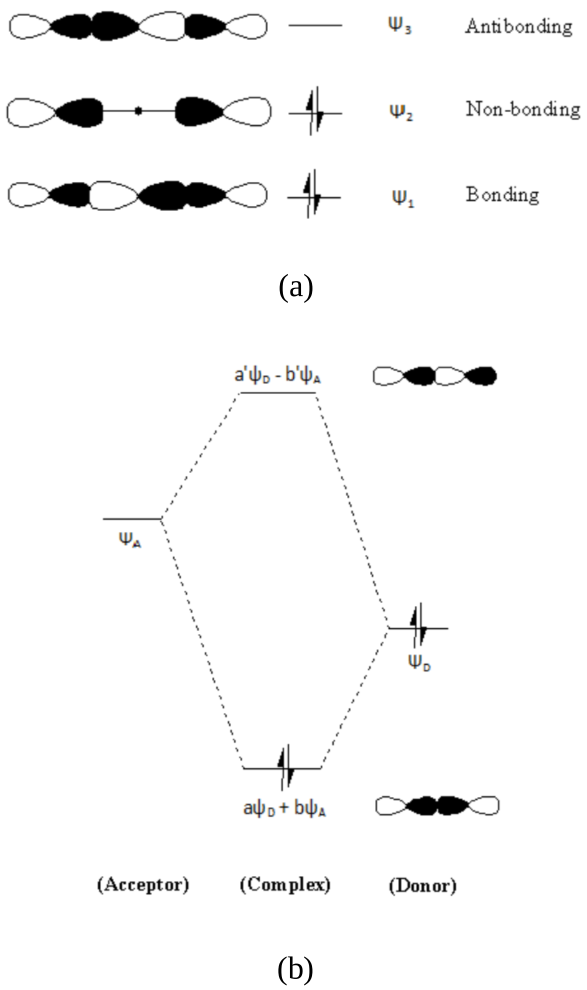


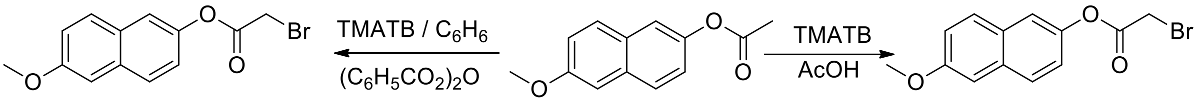
Figure 1.7. (a) Rundle-Pimentel scheme for delocalized three-centre σ bonding (b) Energy level diagram for a two-level donor-acceptor interaction[42,45]

In a two-centre system, a donor-acceptor (also known as a dative bond) bond is usually made up from interaction between a relatively high-lying doubly occupied orbital on the donor fragment and a low-lying empty orbital on the acceptor fragment (figure.1.7. (b)). The HOMO of any complex is formed from the HOMO (highest occupied molecular orbital) of the donor (Ψ_D) and the LUMO (lowest unoccupied molecular orbital) of the acceptor (Ψ_A). Charge transfer from donor to acceptor takes place and the strength of the donor acceptor bond is determined by the stability of the HOMO of the complex relative to the position of Ψ_D. However, in case of three-center systems, due to the presence of occupied orbitals in the acceptor, the donor-acceptor interactions have been observed to be more complicated. The Rundle-Pimentel scheme, though has been interpreted in many ways to understand the nature of bonding in molecules containing an electron-rich three-center bonding or hypervalent central atom, continues to be widely accepted till date and can be used even to understand the bonding in tribromide ion[42,45].

1.2. Application of QATBs as brominating agents

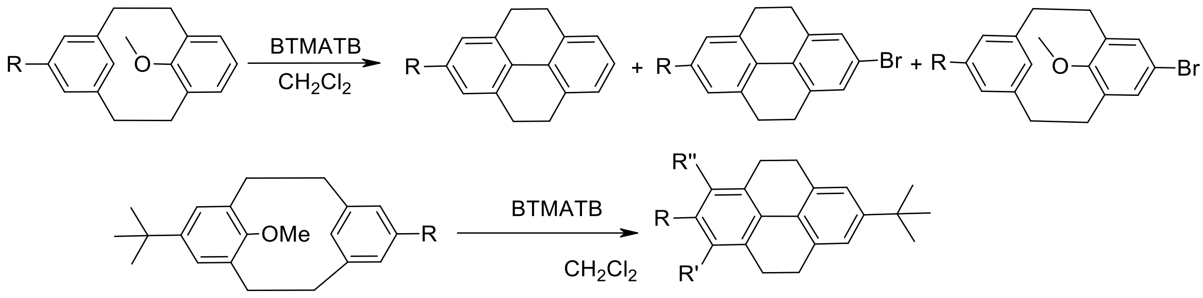
Among the many applications of QATBs, being agents of bromination is the most prominent one and thus a review of their ability as brominating agents is presented below.

TMATB was explored for its brominating property by Avramoff and coworkers[9]. 2-acetyl-5-bromo-6-methoxynaphthalene was the only product when TMATB was reacted with 2-acetyl-6-methoxy-naphthalene in the solvent medium of acetic acid but gave α-brominated product with reaction condition was altered (Scheme 1.1).



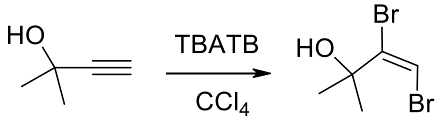
Scheme 1.1.[9]

One of the widely used QATBs for the bromination of various organic compounds is BTMATB which is used for bromination of phenols, aromatic amines and ketones[46–49]. When BTMATB is reacted with 8-methoxy [2.2] metacyclophanedichloromethane, the trans-annular reaction products, tetrahydropyrene and 2-bromo-4,5,9,10-tetrahydropyrene are formed in addition to 5-bromo-8-methoxy[2.2]metacyclophane. Under similar reaction conditions 5-*tert*-butyl-8-methoxy[2.2] metacyclophanes gives tetrahydopyrene derivative exclusively (Scheme1.2)[50].



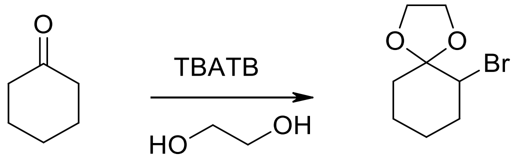
Scheme 1.2.

Another popular brominating agent is TBATB which was first reported by Buckles and coworkers[7]. Berthelot and his team extensively explored TBATB for its bromination ability of various organic compounds. Among various groups of organic substrates, bromination of phenols and amines have been performed in $CHCl_3$ using TBATB to obtain the corresponding *p*-bromo product. Subsequently, TBATB have also been reported for the stereoselective bromination of alkynes, where it produces the (*E*)-isomer exclusively (Scheme 1.3) in CCl_4 solvent medium[51].



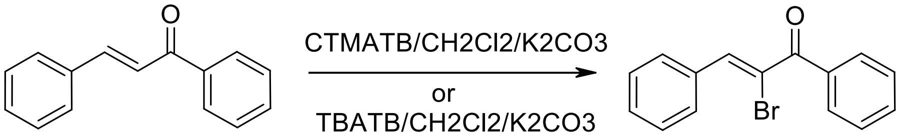
Scheme 1.3.

Furthermore, it was observed that α-bromination of ketones can also be achieved using TBATB, however, when the reaction is performed in the presence of ethylene glycol, keto protection was observed simultaneously (Scheme 1.4)[52].



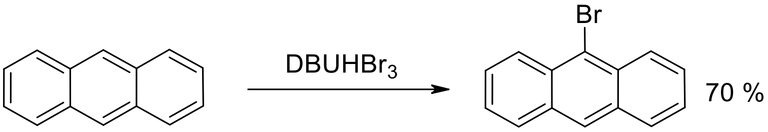
Scheme 1.4.

Thereafter, TBATB and CTMATB was explored by Khan *et al.* for preparation of different various acyclic and cyclic α-bromoenones from the corresponding enones using a convenient and useful method. They reported that the dibromo derivative of enone undergoes elimination giving α-bromoenones in the presence of K_2CO_3 (Scheme 1.5)[53].



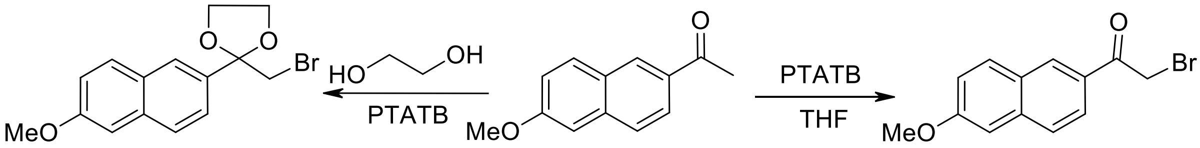
Scheme 1.5.

Another QATB, $DBUHBr_3$ has been reported as an efficient brominating agent for bromination of diverse organic substrates in addition to the ring bromination of anthracene (Scheme 1.6)[21].



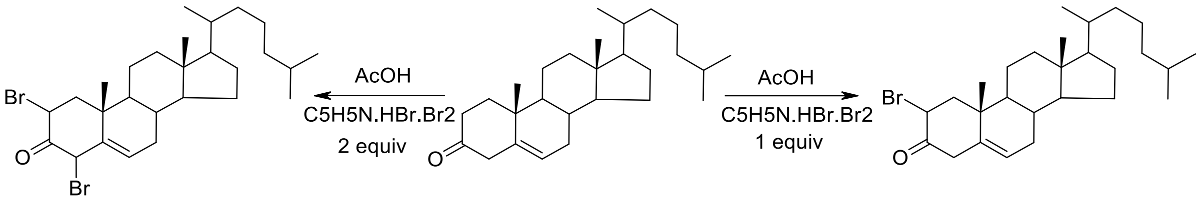
Scheme 1.6.

It has been found that PTATB when dissolved in THF acts a good source of bromine and it differs from bromine in reactivity. Observation revealed that it is comparatively less electrophilic and reactive than molecular bromine in bromination of aromatic rings and double bonds. However, α-Bromination of ketones is preferentially possible in comparison to ring bromination using PTATB (Scheme 1.7)[54,55].



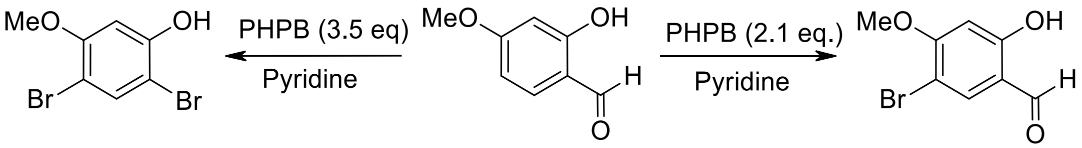
Scheme 1.7.

Djerassi and Scholz reported the selective α-bromination of ketones using PHPB[56,57]. When PHPB was treated with cholestane in 1 and 2 equivalents respectively, it gave the dibromo derivative, 2,4-dibromo cholestanone and 2-bromo cholestanone (Scheme 1.8).



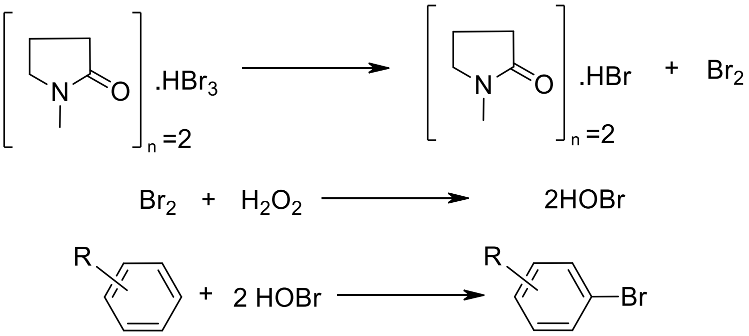
Scheme 1.8.

2-hydroxy-4-methoxybenzaldehyde was treated with PHPB (2.1 equiv., pyridine) to give an 80% isolated yield of 3, 5-dibromo-2-hydroxy-4-methoxybenzaldehyde. However, when 3.5 equiv. of PHPB was used, in the same reaction conditions, a mixture of 2, 4, 6-tribromo-4-methoxyphenol and 3, 5-dibromo-2-hydroxy-4-methoxybenzaldehyde was achieved (Scheme 1.9)[58].



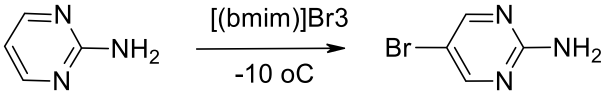
Scheme 1.9.

MPHT have been reported for a regioselective and highly efficient method for the bromination of different aromatic substrates in aqueous hydrogen peroxide. Solely the use of MPHT as a brominating agent resulted in poor product yields, however, enhanced reaction rate and product yields was achieved when aqueous hydrogen peroxide was added (Scheme 1.10)[59].



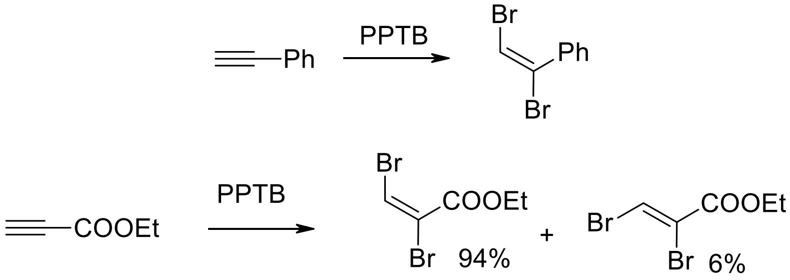
Scheme 1.10.

Thereafter, Chen and group reported the regioselective bromination of anilines using an ionic liquid type tribromide bmimTB which was found to be efficient in this case (Scheme 1.11)[60].



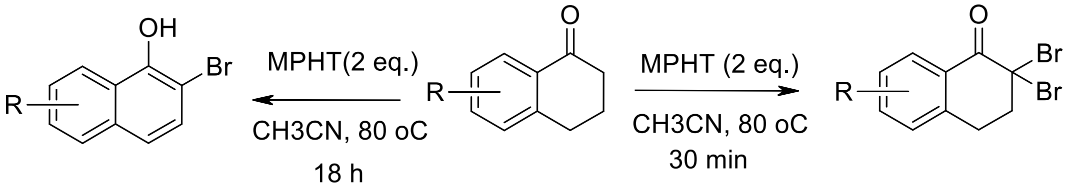
Scheme 1.11.

PPTB has been reported as a 'vapor pressure free' brominating agent for bromination of ketones, aromatics, alkenes and alkynes. Dibromination of phenylacetylene resulted in an excellent yield of only one isomer whereas ethylpropyolate afforded to a mixture of *cis*-*trans* isomers (Scheme 1.12)[18].



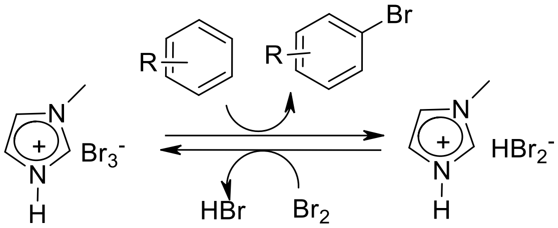
Scheme 1.12.

Provot and co-workers reported the bromination of substituted-1-tetralones using MPHT, and the later has proven as an efficient agent for selective α,α-dibromination of tetralones. Further, when the conditions were base-free and the reaction was continued for a longer time, various 2-bromo-1-naphthols were achieved in good to excellent yields from tetralones in one-pot sequence (Scheme 1.13)[61].



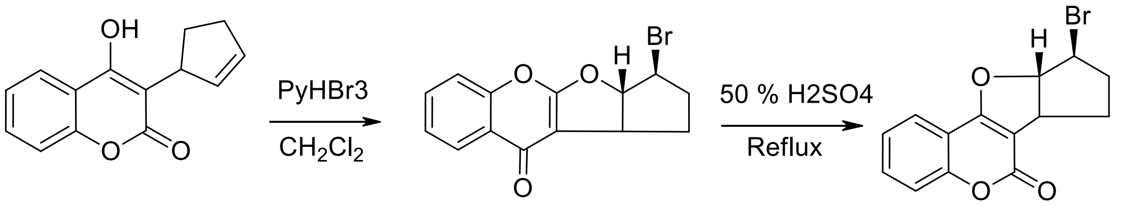
Scheme 1.13

Again, Chiappe *et al.* reported 3-methylimidazolium tribromide [(Hmim)Br_3] for the bromination of aromatic compounds (Scheme 1.14)[62,63].



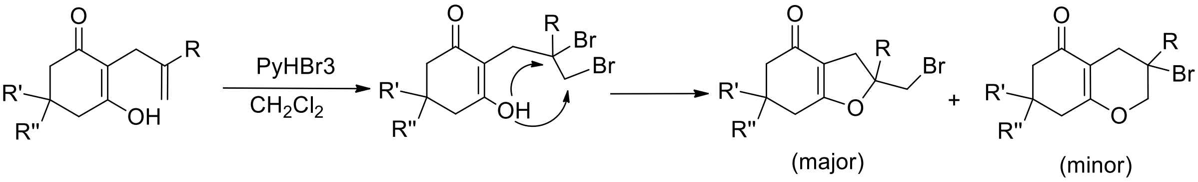
Scheme 1.14

PHPB when used for bromination of 4-Hydroxy[1]benzopyran-2-one or its acetate in dichloromethane at 0-5^{o}C, fused furochromone in 90% yield was obtained. Further, the heterocyclic product undergoes rearrangement to furnish fused furocoumarin in 87% yield (Scheme1.15)[64].



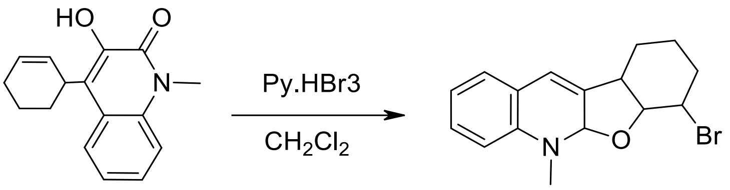
Scheme 1.15.

Thereafter, PHPB has also been reported for the bromination of α-allyl-1,3-cyclohexanediones to give a mixture of 3-bromomethyltetrahydrobenzopyran-5-ones (minor) and bromomethyltetrahydrobenzo furan-4-ones (major) as products (Scheme1.16)[65]. During the reaction a 2-(2, 3-dibromopropyl)-1,3-cyclohexanedione intermediate was formed to give both the endo and exocyclic derivates.



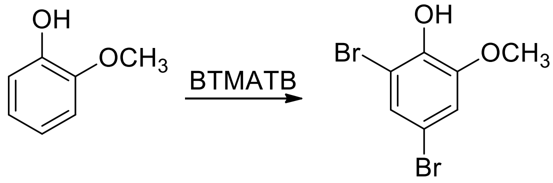
Scheme 1.16.

Majumdar and co-workers have reported PHPB for the conversion of 4-hydroxy [1] benzopyran-2-one into fused furochromone in 90% yield(Scheme 1.17). Rearrangement of this heterocycle takes place to furnish an 87% yield of fused furocoumarin[66].

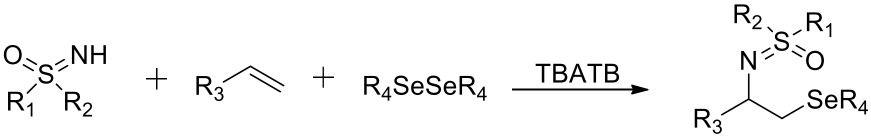


Scheme 1.17.

Liu *et al.*, 2022, reported the conversion of 2-Methoxyphenol to 2,4-Dibromo-6-methoxyphenol using BTMATB as shown in scheme 1.18[67]. Shakurova *et al.*, 2022, reported the one-pot synthesis of pyridinium analogues of lupane triterpenoids using some organic tribromides (Tempo$^+$Br$_3^-$, TBA $^+$Br$_3^-$, Py·HBr·Br$_2$)[68]. Li *et al.*, 2022, reported the synthesis of β-ArylselenoSulfoximines using TBATB as shown in scheme 1.19[69].



Scheme 1.18.



Scheme 1.19.

Role of QATBs in preparation of brominated activated carbon

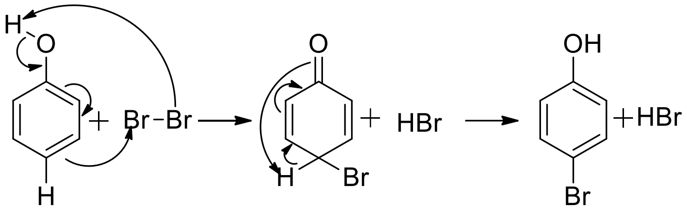
With the advancement of green chemistry, researchers are attempting to modify reaction conditions using greener materials and techniques[70–72]. One of the most important materials in industrial chemistry is the brominated activated carbon, which finds its importance in mercury removal from air and water as well[73–76]. Although many works have reported on the preparation of brominated carbon materials, almost all the research have been focussed on the utilization of bromine (Br$_2$) as the brominating agent[77–80].

However, the limitations of using Br_2 lie in the safety risk involved in the handling of bromine and their toxicity. Therefore, a greener, mild and versatile brominating agent would provide a better alternative over the molecular bromine[81]. An effort has been made to prepare brominated activated carbon using green and cost-effective CTMATB as the brominating agent[82]. They characterized the brominated material using Field emission scanning electron microscopy/energy dispersive X-ray analysis, Fourier transform spectroscopy, powder X-ray diffraction, Brunauer-Emmett-Teller surface area analyzer, and X-ray photon spectroscopy techniques and results indicated towards the formation of C-Br covalent bond.

So far there is only one attempt[82] on the bromination of activated carbon using QATB, however considering the versatility of QATBs, more of them should be explored for their ability in bromination of activated carbon.

1.3. Brief review on earlier mechanistic studies of bromination by QATBs

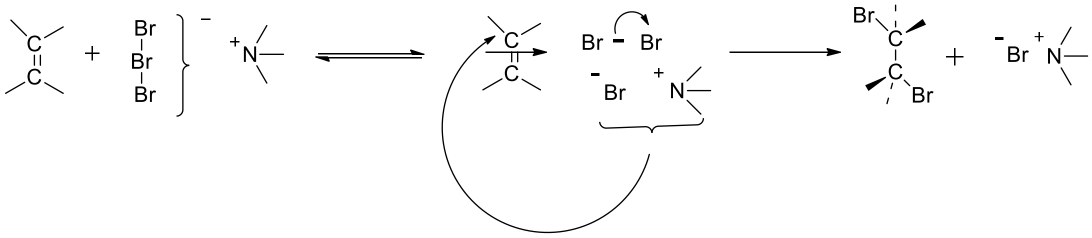
Bromination of aromatic systems is a common reaction because of the important applications of bromo-aromatic compounds[83]. Before the toxicity of bromine was acknowledged, this reagent was most commonly used in bromination reactions, so much so that the bromination mechanism has become a part of organic chemistry textbooks to explain electrophilic aromatic substitution reactions (Scheme 1.20)[84].



Scheme 1.20. Mechanism of bromination of phenol by Br_2 [84]

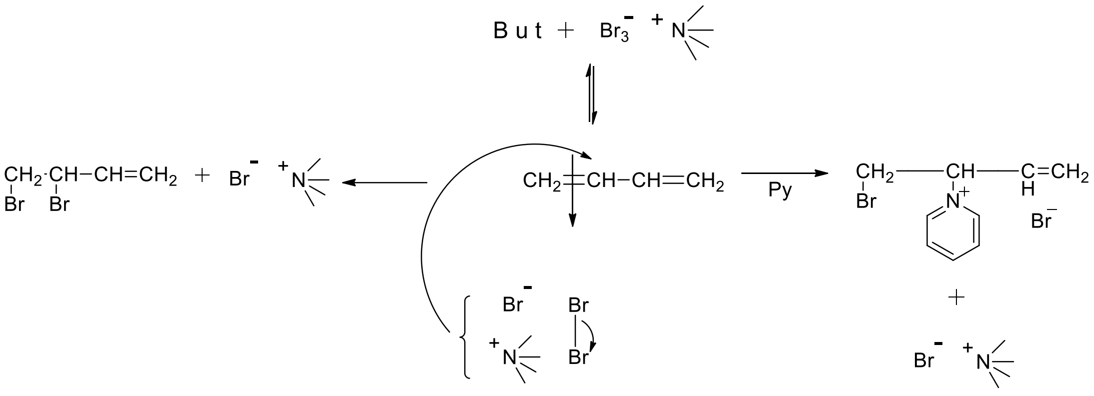
However, with the advent of green chemistry there has been much focus on avoidance of use of hazardous chemicals, and this is how QATBs became popular as environmentally benign alternatives to bromine. Unfortunately, till date it has not been possible to prove the mechanism through which the Br_3^- ion reacts, which is not ideal because it limits the scope for planning of reactions. Though existing reports ambiguously suggest that Br_3^-dissociates into Br^- to Br_2 during the course of a bromination reaction[85–88], after which Br_2 acts as the brominating agent, experimental evidence does not seem to be available to support this assertion.

Literature reports suggest that efforts had been made even earlier to under the mechanistic pathway which QATBs follow. For example, Bellucci *et al.* 1980[85], reported the bromination of ethene using TBATB as shown in the scheme 1.21 below and stated that it is not possible to easily distinguish between a direct electrophilic attack by the Br_3^- and a Br^- assisted attack by Br_2 using kinetics. They further mentioned that a direct electrophilic attack might take place in case of reactive alkenes and Br_2 might be released in case of unreactive alkenes. In their studied reaction, they further reported the detachment of the Br_2 from the Tetrabutyl ammonium bromide (TBAB), following which the Br_2 brominates the ethene.



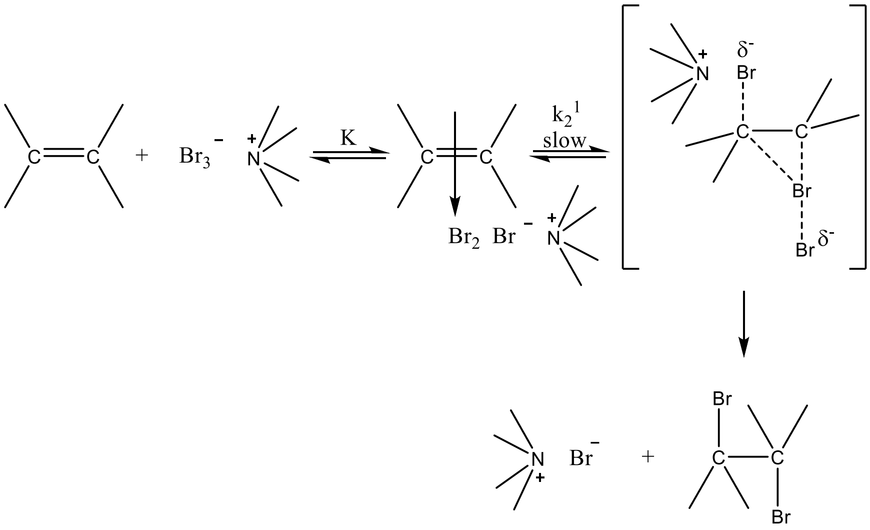
Scheme 1.21. Bromination of ethene using TBATB[85]

Bellucci *et al.* 1981[86], thereafter, reported the bromination of 1,3-Butadiene using TBATB as shown in scheme 1.22 below, and reported similar statements as Bellucci *et al.* 1980[85].



Scheme 1.22. Bromination of 1,3-Butadiene using TBATB[86]

Thereafter, in 1985, Bellucci *et al.*[88], reported the mechanism of addition of the tribromide ion to cyclohexene using TBATB as the brominating agent as shown in scheme 1.23. They stated that multiple reaction pathways are possible for this reaction, however, for their studied reaction, the detachment of Br_2 from TBAB was reported which then brominates the cyclohexene.



Scheme 1.23. Bromination of Cyclohexene using TBATB[88]

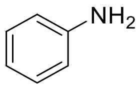
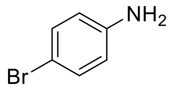
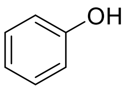
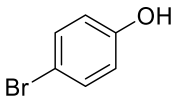
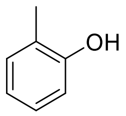
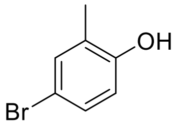
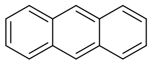
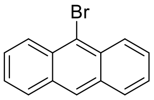
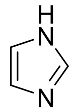
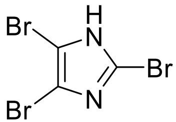
Boer *et al.* 1988[87], in a similar type of study reported that the tribromide ion absorbs light in the UV-region at 268 nm and that molecular bromine is known to be in rapid equilibrium with tribromide ions. Further, they stated that the reaction between tribromide and 2-chlorodimedone is a fast reaction.

1.4. Reaction profile of QATBs in bromination reactions

Over the years, several tribromides have been synthesized ranging from aliphatic to aromatic as well as complex tribromides[89–91]. Again, various aliphatic tribromides of diverse chain lengths have been prepared by different groups and used for different reactions[2,3,83,89]. When reviewing the reactions possible by the QATBs, it can be observed that despite the fact that in all the QATBs, Br_3^- is the reactive species, each QATB shows a different reactivity profile[1,10]. Bora *et al.* 2001, studied the bromination of a variety of organic substrates using TBATB and CTMATB, and reported that both reagents are highly efficient, however they found that CTMATB acted as a better brominating agent than TBATB in their reactions.

Thereafter, Kumar *et al.* 2012[92], studied the bromination of few organics using TBATB, TEATB, CTMATB, and TMATB, under thermal conditions at temperature 60 ± 5^0C, microwave conditions, and at room temperature; the results of which are shown in table 1.1, 1.2, and 1.3 below. As can be seen from the tables, the product profile is different for all the QATBs.

Table 1.1. *Bromination of organic substrates with QATBs under thermal condition at temp. 60 ± 5^0 C.*[92]

Substrate	Product(s)^b	TBATB		TEATB		CTMATB		TMATB	
		r.t.^{a} (min)	%Y^c	r.t.^{a} (min)	%Y^c	r.t.^{a} (min)	%Y^c	r.t.^{a} (min)	%Y^c
		10	75	25	68	8	70	15	68
		15	72	20	64	10	72	15	70
		25	65	10	60	15	60	20	68
		155	80	185	76	125	80	90	72
		10	65	10	55	10	62	25	55

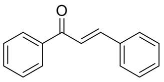
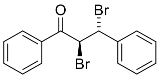
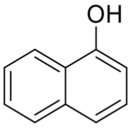
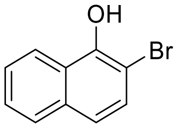
 	70	75	60	62	60	72	45	65
 	15	78	20	70	15	74	25	69

Table 1.2. *Bromination of organic substrates with QATBs under microwave conditions*[92]

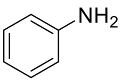
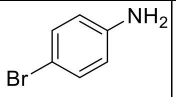
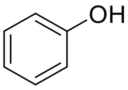
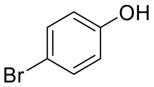
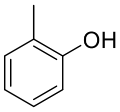
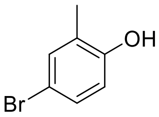
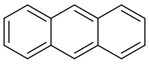
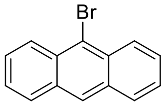
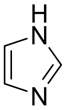
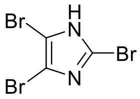
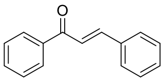
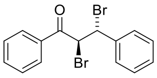
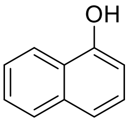
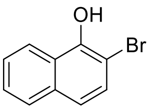
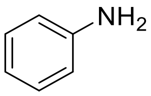
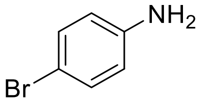
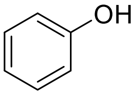
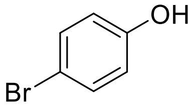
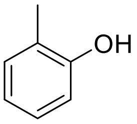
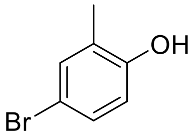
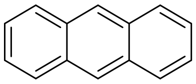
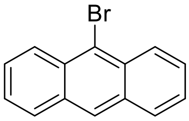
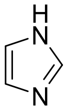
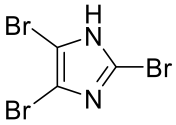
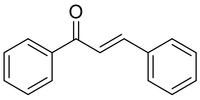
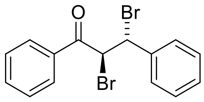
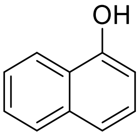
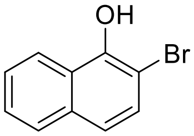
Substrate	Product(s)[b]	TBATB		TEATB		CTMATB		TMATB	
		r.t.[a] (min)	%Y[c]	r.t.[a] (min)	%Y[c]	r.t.[a] (min)	%Y[c]	r.t.[a] (min)	%Y[c]
		60	83	50	80	35	85	30	79
		40	76	30	72	40	78	40	72
		45	80	40	78	35	82	45	76
		80	92	75	85	55	90	60	82
		100	72	20	65	10	78	30	71
		50	87	55	75	45	75	65	68
		25	81	20	79	45	82	30	76

Table 1.3. *Reactions by conventional methods in acetonitrile solvent at room temperature*[92]

Substrate	Product(s)[b]	TBATB		TEATB		CTMATB		TMATB	
		r.t.[a] (min)	%Y[c]	r.t.[a] (min)	%Y[c]	r.t.[a] (min)	%Y[c]	r.t.[a] (min)	%Y[c]
		3h 10 min	72	3.5h	65	3.5h	69	2h 50min	62
		3h 30min	70	4.5h	60	3.5h	68	2h	70
		2h 50min	62	3h 20min	58	3h	60	4h	62
		3h 40min	70	4.5h	68	4.5h	87	4h	72
		4h 20min	68	4h	40	5h	55	3.5h	50
		5h	72	5h	55	5h	92	4.5h	65
		3h	73	4h	65	3.5h	70	3.5h	68

1.5. Role of some common solvents in bromination reactions

1.5.1. Influence of solvents in bromination reactions

Solvents tend to influence the reaction rates of reactions drastically[93–95] i.e., they can speed up or slow down a reaction process, might influence the product yields etc. Each solvent has a different impact on the same reaction, which makes it more interesting to select a suitable solvent for any reaction process.

Bromination reactions are usually conducted in a solvent medium and interestingly, literature reports reveal that a wide range of solvents have been used for the different reactions. Solvents such as acetonitrile[41,96,97], water[98–100], tert-butyl alcohol (t-

BuOH)[101,102], ethyl acetate[103,104], acetic acid[105,106], trifluoroacetic acid (TFA)[107], ethanol[56,108], methanol[108], and dimethyl sulfoxide (DMSO)[109,110] have been used in various studies by different group of workers probably because of their relatively greener nature. However, it is interesting to note that solvents like pentane[111,112], hexane[113,114], heptane[111,115], cyclohexane[116], and carbon tetrachloride (CCl_4)[97,117–120] have also been employed as solvent media in multiple experiments by different research groups despite their reported hazards; which might be because of their enhanced influence in the studied reactions. This brief account indicates that bromination reactions were performed in a diverse variety of solvents and also that both polar and non-polar solvents are suitable for bromination reactions.

Similarly, as per our literature review, bromination reactions using QATBs have been performed in various solvents like acetonitrile, CCl_4, ethyl acetate, dichloromethane (DCM), water etc[96,99,121–123]. Kajigaeshi *et al.*, 1988[121], reported the bromination of aromatic amines using benzyltrimethyl ammonium tribromide using dichloromethane and methanol as solvent media. Akiko *et al.*, 1990[122], reported the bromination of 2-Methoxyphenol using p-Methylbenzyltrimethyl ammonium tribromide in dichloromethane-methanol (5:1) under stirring at room temperature. Teichmannc *et al.*, 1993[123], reported the 1,5-Anhydrohex-1-enitols (Glycals) using TBATB and BTMATB as the brominating agent under various solvent conditions i.e., CCl_4, ethyl acetate, tetrahydrofuran, DCM, and MeCN. Kumar *et al.* 2011[96], reported the bromination of certain organic substrates using Cetylpyridinium tribromide using acetonitrile solvent medium at room temperature. Thereafter, Longkumer *et al.*[99] 2019, reported the bromination of various substrates using CTMATB using water as the solvent medium in microwave conditions.

1.5.1.1. Greenness ranking of solvents and solvent selection guides

As mentioned in the previous section, bromination reactions using QATBs have been reported in a variety of solvent, however, the hazards associated with each solvent have not been considered. The advent of green chemistry has brought with it a huge amount of focus on the hazard considerations of all chemicals which are part of chemical processes[124,125]. Amongst the many types of chemicals, organic solvents have been under continuous scrutiny because of the inherent hazards associated with[126]. A number of solvents under scanner are in fact commonly encountered in day-to-day synthetic organic chemistry. For example, solvents such as pentane, heptane and hexane are hazardous to human health, capable of causing mild symptoms such as skin irritation, dizziness, etc., or more severe conditions like damage of the central nervous system, kidneys or liver[127–129]. Furthermore, these solvents are also highly flammable liquids. Methanol is another highly toxic solvent which causes organ damage and even death when ingested[130], while CCl_4 is an acknowledged carcinogenic chemical[131,132]. Another commonly used solvent is trifluoroacetic acid which is capable of attacking the respiratory tract causing cough, wheezing, and/or shortness of breath[133]. In addition to causing health hazards, most solvents are detrimental to floral and faunal health and therefore pose a threat to the environment. Over and above is the fact that solvents are mostly used in bulk, thereby further amplifying their detrimental effects. Therefore, it becomes imminent that the hazards associated with solvents are very serious and cannot be overlooked.

Even though the hazards associated with solvents advocates for their complete avoidance in synthetic protocols[134], unfortunately however, they are an integral part of most chemical transformations. This is because though solvents are not active components of any chemical formulation, but their role is beyond simply providing a medium for reactions to occur. They are responsible for the solubility and stability of compounds and influence molecular associations of reactants during reactions[135–137].

In view of this, there has been an effort to circumvent the use of hazardous solvents in chemical reactions through the use of more environmentally benign alternatives such ionic liquids, deep eutectic solvents, supercritical fluids, switchable solvents, liquid polymers, and renewable solvents[138]. However, these specially designed solvents have limitations in terms of scalability and cost effectiveness, and therefore even though hazards associated with many conventional solvents continue to be very serious concern, many of these solvents still find usage in organic transformations[138,139].

Acknowledging the fact that traditional solvents cannot be completely done away with, identification of green and sustainable solvents and development of comprehensive tools, techniques and frameworks for solvent selection have become an essential requirement. Since the level of hazard of solvents vary from one another, data sheets or solvent selection guides[138–141] become important because they allow solvents to be ranked based on ease of waste disposal, health, and safety issues, etc. Some chemical companies as well as health departments have developed various safety data sheet which list out the hazards associated with these solvents and the GlaxoSmithKline (GSK) guide[142] is one such useful reference in this regard. The GSK's solvent selection guide has been reported to be a reliable tool for solvent selection and have been referred by various researchers for choosing their solvent of choice[143–145].

1.6. Computational chemistry

Computational chemistry is a branch of chemistry which falls under the scope of theoretical chemistry[146] in contrast to wet lab experiments. Computational chemical methods are created using the principles of quantum chemistry and are an overlap between physics and chemistry[147]. With the advancement of science and technology, the use of computational tools and techniques have increased immensely in various fields like chemical industries, pharmaceutical industries, chemical engineering, environmental science, material science, etc[148]. The reason for the use of computation in these fields might lie in the fact that (a) it is easier to design new compounds computationally, check their properties, in addition to determining their stabilities, (b) various compounds which are difficult to get or expensive to purchase can be studied computationally first to understand their potentials in different applications, (c) chemicals which might be associated with certain hazards can be first rationalized using computational calculations, (d) using computation before proceeding to wet lab experiments will allow the researchers to save time and chemicals as the use of trial and error can be avoided to a great extent. There are numerous electrochemical properties which can be studied computationally; some of which are (1) Electronic structure determinations[149], (2) Geometry optimizations (ground state and excited state)[150], (3) calculations of vibrational wave numbers, IR intensities, IR spectrum[151], (4) Definition of transition structures and reaction paths,[150] (5) Protein calculations, i.e. docking[152], (6) Electron and charge distributions calculations[153], (7) Calculations of potential energy surfaces (PES),[153](8) Calculations of rate constants for chemical reactions (kinetics) [153] (9) Thermodynamic calculations- heat of reactions, energy of activation,[153] (10) calculation of NMR chemical shifts,[151] (11) characterization of molecular orbitals for reactivity predictions, (12) calculation of electronic moments such as dipole moment, polarizability, first order hyperpolarizability, second order hyperpolarizability,[153] (13) calculation of electronic excitations, UV spectrum,[151] (14) calculation of charge distribution on atoms of molecule (MPA, CHELPG, NPA etc.), [153] (15) Calculation of many other molecular and bulk physical and chemical properties, etc[153]. In order to evaluate these properties, there are various computational methods that can be opted for[153].

1.6.1. Computational chemistry methods

Among the different computational methods, the four most important ones are the molecular mechanics method, *ab initio* method, semi-empirical method, and density functional theory (DFT) which are explained briefly below.

1.6.1.1. Molecular mechanics (MM) method

MM also known as force field method is a computational method which uses classical mechanics to determine various properties of a compound such as energies, molecular geometry etc. In this method, the atoms are considered as spheres and the bonds between the spheres are treated as harmonic oscillators, because of which it is comparatively faster than other computational methods. MM computes the potential energy surface of compounds using potential functions which rely on experimental parameters like force constant and equilibrium values. The potential functions are used to explain different types of interactions like bond stretching, angle bending, torsional energies, and non-bonding interactions. They have certain limitations as they are not applicable for electronic properties and are restricted by parameters of equation (i.e., different types of atoms require different force fields)[154,155]. They are most suitable for simulations of large molecules like DNA or protein[156].

1.6.1.2. *Ab initio* method

Ab initio methods are used in computational chemistry and are defined by the principles of quantum chemistry[157]. The meaning of the word "*ab initio*" means "from the first principle" i.e., the energetics and properties of the compounds are calculated as functions of the positions of the nuclei, from first principles without any knowledge of experimental data[158]. Even though, the working equations may be developed using variational principle or perturbation theory, the approximations do not require "fitting" into existing experimental input. The approximations can be gradually enhanced when the level of treatment is raised[159]. *Ab initio* methods approaches to solve the Schrödinger equation in order to provide valuable information like physical and chemical properties, electron densities, and energies of the system[160]. The possibility of achieving “good” results by solving the Schrödinger equation for different types of systems have allowed theoretical chemists to address several problems in many disciplines; the importance of this observation can be reflected by the 1998 Nobel prize awardees, John Pople and Walter Kohn[161].

The Hartree-fock (HF) method is the simplest of all *ab initio* methods, where the Coulombic electron-electron repulsion is not considered exclusively; rather its average effect (mean field) is involved in the calculation. This proceeds through variational principle and thus the approximate energies obtained, which are expressed in terms of wave function, are always greater than or equal to the exact energy[162]. And an increase in the size of the basis set, causes the energy and the wave function to approach a limiting value known as the Hartree-Fock limit[163]. Most of the *ab initio* methods starts with the HF calculations and later is corrected for electron-electron repulsion, called the electron correlation. Most common examples of post-HF methods are the Møller-Plesset perturbation theory (MP2)[164] and coupled cluster theory (CC)[165]. The HF method is inadequate in a few situations, mainly for bond breaking processes; and for post-HF methods, this single-determinant reference function is not a good basis[166]. Therefore, it is important to begin with a wave function that involves more than one single determinant such as multi-configurational self-consistent field and methods have been constructed which use this multi-determinant reference for modifications.

1.6.1.3. Semi-empirical method

Semi-empirical methods are modified HF method, where some parameters are obtained from empirical data which allows the method to include some electron correlation effects.

This method is very popular for larger systems where the HF method without the approximations is computationally more expensive. The *ab initio* methods (including HF) mostly involve the determination of two electron integrals, which is omitted or parameterized in the semi-empirical methods, thereby making the later one much faster[167]. The modern semi-empirical methods approach the modified neglect of differential overlap (MNDO)[168], which involves assigning parameters for different types of atoms and thereby fitting them to reproduce like dipole moments, geometrical variable, first ionization energies, and heats of formation. AM1[168] and PM3[168] are the two the latest versions of the MNDO method. Despite its fast computation, the results obtained from semi-empirical methods can be erratic and generally have a poor reliability.

1.6.1.4. Density functional theory (DFT)

DFT is a method which follows the principles of quantum mechanics to obtain an approximate solution to the Schrödinger's equation of the many-body system. Through this method, the properties of the systems can be evaluated by using functionals, i.e., functions of another function. These functionals in DFT, are spatially dependent electron density. The popularity and versatility of DFT is widespread in the fields of computational chemistry, computational physics, and condensed-matter physics. Nonetheless, until the 1990s, DFT was not considered accurate enough for quantum chemistry calculations, after which the approximations used in DFT were refined greatly to better model the exchange and correlation interactions[169,170]. The cost of computation using DFT is comparatively lower as compared to traditional methods, like, exchange only HF and post HF methods which include electron correlation[171]. In DFT, the energy of a molecule is determined from the electron density rather than the wavefunctions, hence the name[172].

1.6.2. Basis set

Basis set is a set of functions more specifically basis functions which are used to develop molecular orbitals. Basis functions can be composed of atomic orbitals, which is the common preference among quantum chemists, they can be plane waves as well which is frequently used in solid-state chemistry[173]. There are different types of atomic orbitals which can be used during a calculation, like, Slater-type orbitals (STO), Gaussian-type orbitals (GTO), or numerical atomic orbitals. Among these three, the GTOs are the most widely used, considering they allow efficient implementations of the post-HF methods[174].

Some of the common types of basis sets are briefly discussed below.

1.6.2.1. Minimal basis sets

The minimal basis set contains one basis function for each atomic orbital in the atom. A common example of the minimal basis set is the STO-3G where the 3G corresponds to three Gaussian primitive orbitals per basis functions. By simply increasing the basis functions per atom, the basis set can be made larger[175].

1.6.2.2. Split valence basis sets

The split valence basis set contains two sizes of basis functions for each valence orbital like the 3-21G basis set. The double-zeta split-valence introduced by Pople is the 6-31G where CGTO is the core orbital made of 6 Gaussian functions, and the two orbitals- one CGTO made of 3 Gaussians and 1 single Gaussian describe the valence orbital[176].

1.6.2.3. Triple split valence basis sets

Triple split valence basis set involves contracted functions of three sizes for each orbital type like the 6-311G basis set, where the size can be altered but not the shape. The 6-31+G is the 6-31G in addition to the diffuse s and p functions for non-hydrogen atoms; but 6-31++G contains diffuse functions for hydrogen as well[177].

1.6.3. Polarizable continuum model (PCM)

The PCM is a computational chemistry method used to create solvation models, which have had many modifications over the years. It is important to consider the solvent models as continuum rather than individual molecules as otherwise computational cost will be extremely high. In the PCM, the solvent is treated as a polarizable dielectric medium represented by a dielectric constant, ε, where the solute is positioned in a cavity surrounded by the solvent. The charge density of the solute polarizes the dielectric medium of the solvent that generates a reaction electrostatic potential which then reacts on the solute itself. Thereafter, the reaction potential of solvent is added to the quantum Hamiltonian of the solute, thereby expressing a new solute charge distribution. This process is iterated until self-consistency is achieved which is regarded as self-consistent reaction field (SCRF)[178].

1.6.4. Gaussian

Gaussian is a computational software which is used in various branches of science like chemistry, physics, engineering, biochemistry etc. The software was first released by John Pople in 1970 and since then it has been modified continuously. The latest version of the Gaussian software is the Gaussian16 which is a precursor of Gaussian70, 76, 80, 82, 86, 88, 90, 92, 92/DFT, 94, 98, 03, and 09. It is a state-of-the-art software suite for the calculation of electronic structures and is licensed for a wide variety of operating systems. Gaussian follows the principles of quantum mechanics and various types of calculations can be done using the Gaussian software by opting different methods and levels of theory. Some of the most common calculations that Gaussian can perform are energy predictions, structural geometry, spectroscopic simulations, predicting reaction pathways etc[153,179,180].

1.6.5. GaussView

GaussView is a platform for designing input files for Gaussian and later to study the output files graphically that the Gaussian software will generate. GaussView itself does not facilitate the calculations involved with Gaussian, rather it acts as a front and back-end interface for Gaussian. The latest version of the GaussView software is the GaussView6 and it is an extremely versatile and user-friendly graphical user interface for modelling and studying chemical structures. It is very comfortable to draw large molecules, then rotate, translate, and zoom in with a few clicks on the mouse. GaussView also allows the importing of standard file formats of molecules such as MDL or MOL files. It simplifies the process of complex input preparation for various types of calculations like routine jobs and more advanced jobs like QST2/QST3 transition structure optimizations, ONIOM, CASSCF calculations, etc. It is also possible to launch a job through GaussView after building the structure, provided the Gaussian software is installed on the same system. Among the various types of calculations whose results can be viewed and examined through the GaussView software, some are pointed below:

- Optimized molecular structures.
- Dipole moment.
- Molecular orbitals.
- Bond lengths.
- Bond angles.
- Atomic charges.
- IR, Raman, NMR, VCD and other spectra.
- Animation of the normal modes corresponding to vibrational frequencies.
- Animation of geometry optimizations, IRC reaction path following, potential energy surface scans, and ADMP and BOMD trajectories[180].

1.6.6. Some common Gaussian calculations

1.6.6.1. Molecular geometry optimization

Molecular geometry optimization involves the three-dimensional arrangement of the atoms in a molecule by minimizing the energy of the system to predict its conformation. Geometry optimization (in principle) simplifies the understanding of molecular binding as well as bond breaking depending on the type of elements involved. In quantum chemistry, it is extremely vital to correctly predict the most stable arrangement of atoms in a molecule, as it is the initial point for various simulations of molecular properties and any further calculations rely on the appropriate structure. Molecular optimizations can be performed using different methods and basis sets depending on the type of structure [150,181].

1.6.6.2. Vibrational frequency analysis

The vibrational frequency analysis of any system in the Gaussian software provides the Infrared and Raman spectra of the studied compounds along with the details of each vibration mode with animation. These data are extremely useful in confirming the peak positions of known compounds as well as newly modelled compounds. The vibrational frequency calculations also help in understanding the nature of stationary points, thereby, to justify the absence or presence of any imaginary frequency, which is important for understanding the stability of the engaged systems[182,183].

1.6.6.3. Dipole moment (μ)

Dipole moment is the defined as the net polarity of a compound, identified as vectors as they possess both magnitude and direction, and measured in Debye. Dipole moment suggests the charge separation in a molecule and a larger difference in electro negativities of bonded atoms means a larger dipole moment. They can arise from two ions in an ionic bond or from atoms in case of a covalent bond. The polarity of a molecule is intensely important for diverse physicochemical properties as understanding the solubility of molecules (either they will be soluble in polar or non-polar solvents). Further, in physics, the dipole moment provides information about the dielectric constant and conductivity of substances[184,185].

1.6.6.4. HOMO and LUMO analysis and their energies

HOMO and LUMO are molecular orbitals where HOMO is the highest occupied molecular orbital and LUMO is the lowest unoccupied molecular orbital. They are collectively regarded as frontier orbitals as these molecular orbitals are at the border between occupied and empty i.e., the HOMO has electrons while the LUMO does not.

The energy gap between the HOMO and LUMO is called as the HOMO-LUMO gap and this gap serves as one of the most important parameters in understanding the reactivity of different compounds. If this gap is large then it will be energetically unfavourable to add electrons to a high-lying LUMO from a low-lying HOMO, and thus, compounds with very high HOMO-LUMO gaps are kinetically stable and exhibit lower chemical reactivity. It is very simple to determine and compare the reactivity of different compounds by just evaluating their HOMO and LUMO energies. Apart from suggesting the reactivity of organic compounds, knowledge of these frontier orbitals also helps in predicting the addition of π ligands in organometallic chemistry. Furthermore, in material chemistry, the HOMO and LUMO orbitals are considered to understand various physical and chemical properties of the studied materials[186,187].

1.6.6.5. Atomic charges

Atomic charge of any compound is one of the most important factors for explaining their molecular properties and reactivity quantitatively. Despite their importance, atomic charges are not observables; i.e., they cannot be calculated definitively by either experiments or quantum chemical calculations. Therefore, various atomic charges schemes have been developed over the years, each one with different partitioning methods for the total density of electrons to one-atom contributions[188].

Mulliken charge is the most common method for determining the atomic charge and they are based in the local electron density; it highly depends on the basis set and the functionals, as it is sensitive to probability density. Thereafter, natural bond orbital (NBO) analysis is also a valuable tool for assigning atomic charges where it calculates the distribution of electron density in atoms and in bonds between atoms. One more important population scheme is the Hirshfeld charges; the difference between the molecular and unrelaxed atomic charge densities is the deformation density, which is how Hirshfeld charges are defined. Among many populations schemes, the Merz-Singh-Kollman (MK) scheme is one of the best schemes for assigning atomic charges, where the charges on atoms are fitted to reproduce the molecular electrostatic potential (MEP) at several locations around the studied compound[189,190].

1.6.6.6. Global reactivity descriptors

Global reactivity descriptors are electronic parameters derived from computational calculations and are used for understanding various relationships between the structure, reactivity, and stability. The ability of prediction of these relationships depends on reliable approximations of these descriptors[191]. The fundamental equations for the global reactivity descriptors involve the energies of HOMOs and LUMOs of the studied compounds as the primary components. Therefore, it is important to determine these energies using appropriate methods and basis sets. Some of the most common global reactivity descriptors are chemical hardness (η), chemical potential (μ), and electrophilicity (ω). Chemical hardness is the ability of a compound to resist to chemical changes in its electronic configuration. Chemical potential is the measurement of an electron's inclination to leave a molecule. And lastly, electrophilicity can be described as the ability of a compound to accept a pair of electrons[192–194].

1.7. Scope and objectives of the work

Quaternary ammonium tribromides have been widely acknowledged in the literature as effective agents for bromination, oxidation, and other organic transformation. However, despite their widespread popularity, a thorough understanding of their structure and reactivity has not yet been achieved. This is crucial since it will enable researchers to determine the compounds' electronic characteristics and to create and improvise reaction conditions. In light of this, an effort has been made through this thesis to address a number of ambiguities regarding the structure and reactivity of QATBs, like the structure and nature of the bonding in the tribromide ion, efficiency of different tribromides in different types of bromination reactions, the mechanistic pathway of bromination by QATBs, and influence of different solvent in bromination reactions by QATBs. The study was conducted to develop a theoretical background for QATBs which is expected to aid researchers to tune reactions according to their needs and to explore QATBs for further applications. Accordingly, the objective for this work was designed in the following way:

1. To study the structure and bonding in QATBs
2. To compare the efficiencies of two different QATBs in bromination reactions
    - 2.1. Bromination of organic substrates
    - 2.2. Bromination of activated carbon
3. To understand the Mercury adsorption ability of the brominated activated carbon
4. To study the mechanistic pathway of bromination by QATBs
5. To rationalize the efficiency and greenness of solvents in bromination reaction by QATBs

1.8. References

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Chapter 2

Determination of the Electronic Structure and Bonding in Tribromide Ion of QATBs

This chapter presents the development of molecular orbital diagram of the tribromide ion in order to understand the nature of bonding in the same. Further, a complete structural assessment of the tribromide ion was performed both in isolated form as well as in presence of certain quaternary ammonium cations to rationalize the effect of the respective cations on tribromide ion.

A part of this chapter has been published in:

Journal of the Indian Chemical Society, **2022,** Volume 99, Issue 8.

2.1. Introduction

2.1.1. Importance of understanding the nature of bonding and structural geometry of any compound

The nature of bonding in any compound is one of the most vital components in understanding the shape of molecules as well as their chemical nature. Chemical bonding is a fundamental notion in chemistry that is crucial to comprehend material structures, characteristics, and reactions[1–3]. However, the concept of chemical bond is totally theoretical in that it does not correspond to any clearly visible phenomena[4,5]. The idea of chemical bond was developed by researchers to explain the events seen in the laboratory using a complex collection of submicroscopic models of matter[6]. Chemical bonding allows scientists to select from the 100-plus elements of the periodic table and mix them in a variety of ways to efficiently create chemical compounds and materials for diverse applications[7].

Similarly, another important aspect of any chemical compound is its chemical structure which should be determined with precision in order to achieve certain crucial information about the compound. Chemical structure depicts the spatial arrangement of atoms and chemical bonds in a molecule, which dictates its molecular geometry. Chemists can see a visual depiction of a chemical formula in this way[8]. Further, a detailed information about the structural geometry of chemical compounds allows researchers to develop reaction mechanisms and predict various chemical and physical properties of the same[9]. Biological activities like antimicrobial action, etc., can also be predicted by analyzing the chemical structures of compounds before proceeding to experimental analysis[10,11]. Toxicity can also be predicted by evaluating the chemical structures of certain compounds as the properties are contained in their chemical structure[12–16]. Other branches of chemistry which require precise structural representation are cheminformatics and QSAR modelling where, even the smallest change can lead to high error rates in results[17].

2.1.2. Structure and bonding in trihalides

The bonding in trihalides in general had been studied by Pimentel and Rundle five decades ago on the basis of molecular orbitals and by considering a delocalized three center σ-bonding (one bonding, one non-bonding and one anti-bonding molecular orbital)[18,19]. Thereafter different reports have attempted to explain the nature of stability of the long bonds by suggesting that in trihalides, there are four electrons, of which two occupy the bonding molecular orbital and another two electrons occupy the non-bonding molecular orbitals thereby resulting in one bond spread over two positions (bond order of 0.5)[20]. There are a number of reported studies on the nature of bonding in hypervalent species with reference to triiodide. For instance, Landrum *et al.*[21] has reported the nature of bonding in trihalides, mixed trihalides and hydrogen bihalides by employing idea of molecular orbital (MO) theory and density functional theory (DFT) calculations and concluded that the bonding in these diverse anions can be understood in terms of Rundle-Pimental model for electron-rich 4-electron-3-centresystem (4e-3c). Almost after a decade, Aragoni *et al.*[20] has reported the nature of bonding in I_3^-, mixed chalcogen/halogen and trichalcogen by employing the same rule and found that these systems account for a total bond order of 1. However, there is a lack of literature, on describing the chemical nature when it comes to tribromide ions. Over the years, different groups including ours have been working on different aspects of QATBs[22–29]. During the course of our studies, we have observed that there exists a lacuna in the understanding of the bonding in this anionic moiety.

Based on literature reports it is understood that in case of I_3^-, the structure is slightly distorted from linearity and the central iodine is non-equidistant from the terminal iodine atoms[18,30]. In order to ascertain if there is any similarity between I_3^- and Br_3^-, reference was made to one of our earlier crystallographic studies which had been done on one of the quaternary ammonium tribromide (QATBs) *viz*., Tetrapropyl Ammonium Tribromide (TPATB), and the single Crystal XRD results indicate that the Br_3^- is also non-linear and the central bromine atom is non-equidistant from the terminal bromine atoms[25]. Since further studies were needed in order to conclusively determine the structure and bonding in the tribromide moiety, through this piece of work, an attempt has been made to understand the electronic structure of the Br_3^- ion and the bonding between the three bromine atoms.

2.1.3. The tribromide ion

The tribromide ion (Br_3^-) is the anionic part of QATBs and is the active brominating agent responsible for bromination of diverse group of substrates. It has played important roles in various organic transformations which have been well reported in literature[31–35]. Despite its popularity, there seems to be a lacuna in understanding the nature of bonding in the Br_3^- which is highly significant to determine important physical and chemical properties such as magnetism, stability, electrical conductivity, UV-Vis Spectroscopic data analysis, etc[36]. There is also lack of comprehensive knowledge about the structural geometry of Br_3^-, which is a vital factor for modifying reaction conditions.

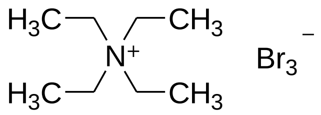
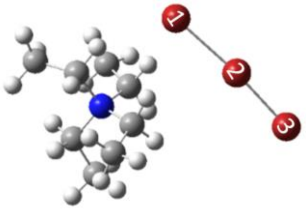
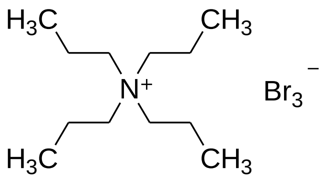
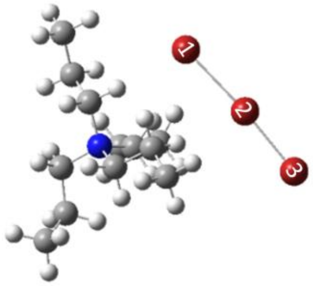
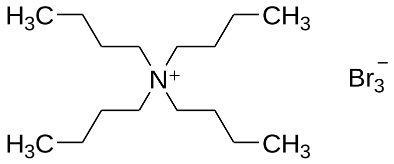
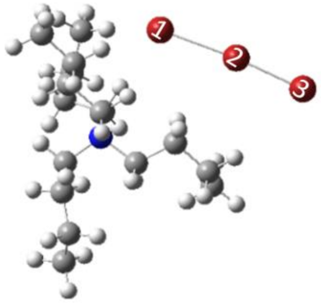
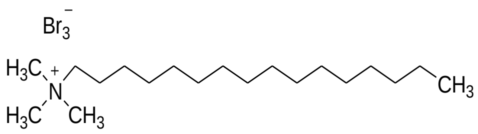
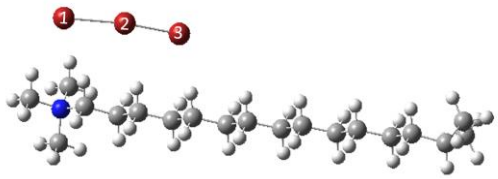
An effort has been made to build the molecular orbital diagram of Br_3^- by using donor-acceptor bonding theory, which might help explain the exact nature of bonding in tribromide. Thereafter, density functional theory (DFT) calculations have been employed to determine the bond length, bond angle and Mulliken atomic charges of Br_3^- and thereby to rationalize the results obtained. The results of this study are expected to find future applications in understanding the mechanism of bromination reactions by QATBs which is a long due question.

2.2. Materials and methods

All the structures were built in the GaussView6[37] visualization software which were then subjected to optimization on the Gaussian16[38] suite of program. The method B3LYP hybrid functional was used along with 6-311G++(d,p) basis set. This basis set is of triple-ζ quality used for valence electrons with diffuse functions and therefore, is appropriate for geometry calculations of ions and chemical species containing lone pair(s) of electrons. Further, the optimized geometries were subjected to vibrational frequency analyses in order to determine the nature of stationary points and to elucidate the zero-point energies. The characteristic of local minima was confirmed by looking into the matrices of energy second derivatives (Hessian) which showed no imaginary frequency.

Subsequently, for building the MO diagram of Br_3^-, the structures of Br_3^-, bromine molecule (Br_2) and bromide ion (Br^-) were optimized and the valence orbitals were observed in order to rationalize their involvement in the donor-acceptor bonding. Furthermore, the QATBs, tertraethyl ammonium tribromide (TEATB), TPATB, tetrabutyl ammonium tribromide (TBATB), and cetyl trimethyl ammonium tribromide (CTMATB) are taken into consideration to understand the structure of Br_3^- in QATB systems. The respective chemical and optimized structures of Br^-, Br_2, Br_3^-, TEATB, TPATB, TBATB, and CTMATB are shown in table 2.1. below.

Table 2.1. *Chemical and optimized structures of Br_3^-, QATBs, TEATB, TPATB, TBATB, and CTMATB*

Abbreviations	Chemical structure	Optimized structure
Br^-	Br^-	
Br_2	$Br-Br$	
Br_3^-	$[Br-Br-Br]^-$	
TEATB		
TPATB		
TBATB		
CTMATB		
Color Code : Br N C H		

The parameters that are studied from the above optimized structures are:

2.2.1. Bond lengths

The bond length of N-Br1, Br1-Br2 and Br2-Br3 were determined in order to understand the symmetry of the tribromide ion in the QATB systems.

2.2.2. Bond angles

The bond angle between Br1-Br2-Br3 was observed in all the QATBs to evaluate if the tribromide ion is linear or bent in the presence of the QA^+ ions.

2.2.3. Atomic charges

The Mulliken charges in each Br atom was checked for understanding the charge distribution in the tribromide ion.

2.2.4. Orbital energies

The orbital energies of Br_3^-, Br_2, and Br^- were recorded for developing the MO diagram of Br_3^-.

The Br atom nearest to the N atom is designated as Br1, consecutively, the central Br atom is considered as Br2 and the Br atom farthest away from the N atom as Br3.

2.3. Results and discussion

2.3.1. The MO diagram of Br_3^-

The tribromide ion was studied to understand its bonding through MO diagram. The MO diagram provides information about the way orbitals take part in the bonding which is a vital step for understanding a molecule at the electronic level. It is crucial to study compounds at electronic level so as to plan experiments by predicting the product that might form and perform further experimental studies.

It is known that bromine can form higher valencies upon excitation, and these valencies logically arise by promoting electrons from filled p and s-levels to empty d-levels resulting in unpaired electrons[39]. These unpaired electrons become very reactive and cause the moiety to form a stable ion by taking up an electron, which becomes possible because of the electron affinity of bromine atom (80.5±0.4 kcal/mol)[40] and also because of its oxidation potential. The t_{1u} orbital of bromide then takes part in the formation of tribromide as a two-electron donor to the acceptor Br_2. In order to develop the molecular orbital diagram, we can take cues from the 4c-3e approximation that was suggested by Rundle-Pimentel, and accordingly state that the Br_3^- ion is formed by the combination of Br_2 molecular orbitals and Br^- atomic orbitals. Thereafter, in order to propose the MO diagram of Br_3^-, we first consider the MO diagram of Br_2 molecule which is shown below in figure 2.1.

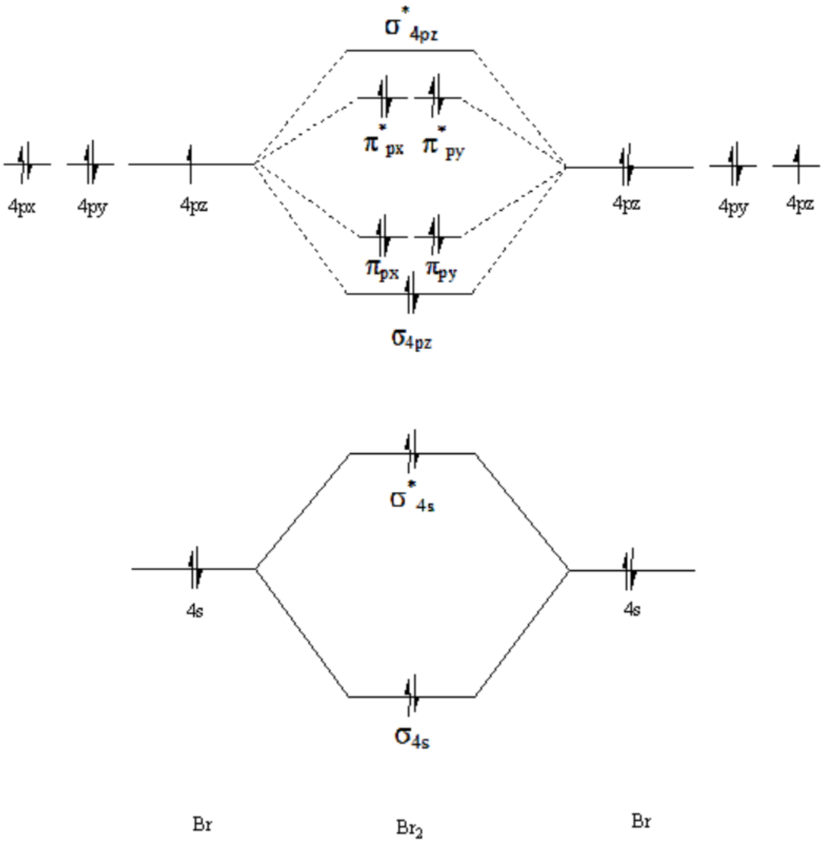


Figure 2.1. MO diagram of Br_2

According to the molecular orbital diagram of Br_2, the inner shell of Br_2 is non-bonding since the orbitals π_{px} and π_{py} and their corresponding antibonding orbitals, π_{px}* and π_{py}* are completely filled and are not expected to take part in the MO of Br_3^-. This leaves a σ-bond from the filled σ_{4pz} orbital, and since there are no electrons in the corresponding antibonding molecular orbital (σ_{4pz}*), thus these orbitals will take part in bonding with Br^- as highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) of the acceptor respectively.

The MO diagram of Br_3^- forming from Br_2 and Br^- is presented based on the DFT results of orbital energies of the three species as shown in figure 2.2. The diagram is built without inclusion of the 3d orbitals of Br^- since they do not take a major part in the donor-acceptor bonding[41]. Furthermore, the π system of Br_3^- is also neglected in the MO diagram since all of them are wholly occupied and might not provide vital information about the nature of bonding in the same. The σ system of Br_3^- has three orbitals, namely Ψ_1, Ψ_2 and Ψ_3, two of which are occupied. Thus, the MO diagram of Br_3^- was constructed from the σ_{4pz} and σ_{4pz}* orbitals of Br_2 and t_{1u} orbital of Br^-. The energies of σ_{4pz} and σ_{4pz}* were determined from the optimized structure of Br_2 and are found to be -4.24 eV and -11.80 eV respectively. The energy of the orbital t_{1u} as determined from the optimized structure of Br- was found to be -0.84 eV. The energies of the three sigma orbitals, Ψ_1, Ψ_2 and Ψ_3, are -0.69 eV, -3.33 eV and -6.52 eV respectively.

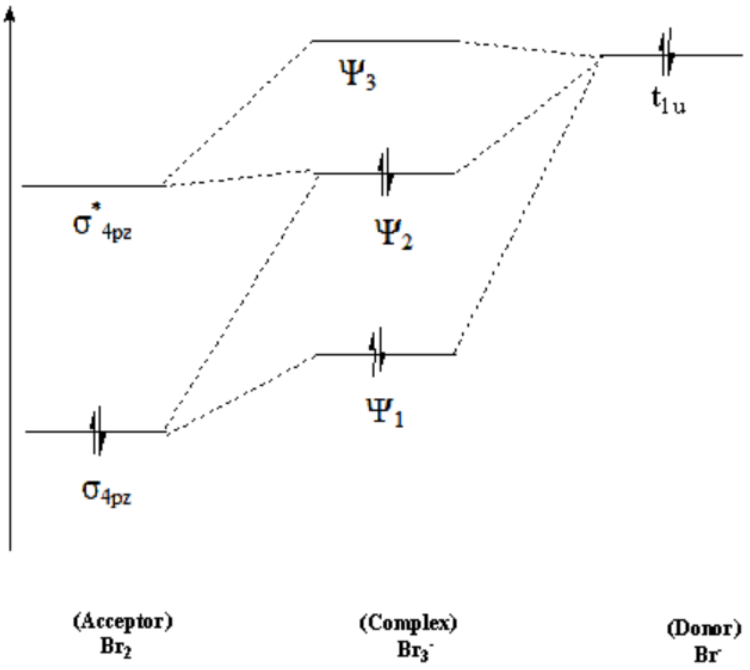


Figure 2.2. MO diagram of Br_3^- forming from Br_2 and $Br^−$

As can be seen from the MO diagram (figure 2.2), the MO of $Br_3^−$, Ψ_1, is formed from the combination of HOMO of Br_2 (σ_{4pz}) along with a minor contribution from HOMO of $Br^−$ (σ_{4pz}*). The HOMO of Br_3^-, Ψ_2, is formed from mixing of both σ_{4pz} and σ_{4pz}*. The LUMO of Br_2, σ_{4pz}*, serves as the significant acceptor orbital and the amount of its mixing in Ψ_2 determines the stability of the complex. Ψ_2 may be highly antibonding if the contribution of σ_{4pz}* is too less in Ψ_2, because of the antibonding contribution of σ_{4pz}. This may cause weakening of the net bonding character thereby resulting in an unstable complex. However, when there is a proportionate mixing of σ_{4pz}* into Ψ_2, the complex will be stable as the antibonding component will be reduced between Br_2 and $Br^−$.

On the other hand, when the $Br_3^−$ complex is formed, a net transfer of electrons from $Br^−$ to Br_2 takes place. Since, the HOMO of the $Br_3^−$ is created from the contribution of σ_{4pz}*(which is vacant in free Br_2), Br_2 gains an electron. The $Br^−$ loses its electrons due to the contribution of t_{1u} into the LUMO of the complex, Ψ_3. Furthermore, the bonding in Br_2 will weaken due to the partial involvement of the antibonding orbital of Br_2, i.e., σ_{4pz}*. From the optimized structure of Br_2, the bond length Br-Br was found to be 2.33 Å, however in case of Br_3^-, this bond length increases to 2.63 Å, thereby justifying the bond weakening in Br_2. Subsequently, it was seen that the two terminal Br atoms are equidistant from the central Br atom in Br_3^-. Thus, it can be said that there is a sizable mixing of σ_{4pz} and σ_{4pz}* in Ψ_2 resulting in the stabilization of the Br_3^- complex.

2.3.2. The electronic structure of Br_3^-

DFT calculations were performed to optimize all the concerned structures to their ground states, so as to evaluate the electronic parameters of Br_3^-. After optimization, it was observed that the structural geometry of isolated Br_3^- was linear, where the distance between the two terminal bromine atoms from the central bromine atom was 2.63 Å. Both the terminal bromine atoms have same atomic charges of -0.473, and the central atom bears a charge of -0.053. However, in QATB systems, the geometry of Br_3^- seems to differ from its isolated state. In all the QATBs, the terminal bromine atom closest to the nitrogen atom is the most negatively charged having charges of -0.611, -0.617, -0.623, and -0.592 in TEATB, TPATB, TBATB, and CTMATB respectively. Interestingly, it is also observed that the central bromine atom which is negative in isolated Br_3^-, is positive in the QATBs with respective charges of 0.049, 0.055, 0.067, and 0.054 for TEATB, TPATB, TBATB, and CTMATB. And the terminal bromine atom which is the farthest away from the nitrogen atom have charges of -0.335, -0.339, -0.331, and -0.346 over them for TEATB, TPATB, TBATB, and CTMATB respectively. Subsequently, it was observed that in QATBs there is alteration in the bond lengths as well. As presented in the table 2.2, the Br1 atom is more attracted towards the nitrogen atom since the bond length Br1-Br2 is longer than Br2-Br3 in case of all the QATBs. The reason for this could be because of the distribution of the electrons to form an ionic bond between the N-atom of ammonium and Br1 of tribromide. Further observation of the structural geometry of Br_3^- revealed that its geometry is distorted from its original linearity in the cases of all the QATBs. The cause of this distortion could be the formation of a N-Br1 bond leading to the shift of electron cloud towards the Br1 thereby attaining a slightly bent shape. Another reason for the change in geometry might be due to the steric hindrance caused by the bulky group of the ammonium moieties. Therefore, from these observations, it can be said that the tribromide ion, in presence of a quaternary ammonium ion loses its linearity, and attains a bent shape with unequal charges in the terminal bromine atoms, and unequal bond lengths Br1-Br2 and Br2-Br3. These results give scope for further studying the mechanistic pathway of bromination reactions by QATBs.

Table 2.2. *Mulliken charges, bond lengths, and bond angles of* Br_3^- *ion in TEATB, TPATB, TBATB, and CTMATB*

QATBs	Mulliken charge (au)			Bond length (Å)		Bond angle (Degrees)
	Br1	Br2	Br3	Br1-Br2	Br2-Br3	Br1-Br2-Br3
Br_3^-	-0.473	-0.053	-0.473	2.63	2.63	180
TEATB	-0.611	0.049	-0.335	2.83	2.56	174.74
TPATB	-0.617	0.055	-0.339	2.82	2.56	175.49
TBATB	-0.623	0.067	-0.331	2.83	2.56	175.27
CTMATB	-0.592	0.054	-0.346	2.80	2.57	174.25

2.4. Conclusion

The study showed that the bonding in tribromide ion can be explained in terms of donor-acceptor interactions. The bonding is a result of interaction between Br_2 and Br^- ion where Br_2 acts as the acceptor and Br^- as the donor. The bonding between Br_2 and Br^- results in decrease in net bonding character in the Br_2 molecule. DFT results revealed that in the case of QATBs, the tribromide ion is non-linear, and the central bromine atom is non-equidistant from the terminal bromine atoms. This distortion from its original symmetrical structure might be because of steric hindrance from the bulky groups in the cations. It is expected that this study will set a foundation for understanding the mechanistic pathway of bromination reaction by QATBs.

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Chapter3

Understanding the Structure – Reactivity Correlation of Different QATBs in Bromination Reactions

This chapter presents the details of a comparative study of two QATBs for their efficiency in bromination reactions on a diverse variety of substrates. Wet lab experiments were performed to determine the product yield and reaction time and this was followed by DFT studies to determine various electronic parameters like dissociation energy, HOMO-LUMO energy gap, and dipole moment of the studied reagents.

The work described in this chapter has been published in:

Chemical Physics Letter, **2018,** Volume 711, Pages 118-126.

3.1. Introduction

3.1.1. Structural variation in QATBs

Quaternary ammonium tribromides (QATBs) have been explored for their applications since nearly a century now and over the years their several types have been synthesized, ranging from aliphatic to aromatic as well as complex tribromides, which have been reported for various applications[1–3]. Goswami *et al.*[4] reported the use of benzyltrimethyl ammonium tribromide (BTMATB) as an oxidizing agent whereas the same reagent has been reported by Kajigaeshi *et al.*[5] as a brominating agent for phenolic derivatives. Some other QATBs like phenyltrimethyl ammonium tribromide (PTMATB)[6], 1,8-diazabicyclo [5,4,0]-tetrabutylammonium tribromide[7,8], hexamethonium bis(tribromide)[9] etc., have also been explored mostly for their use as brominating and oxidizing agents[6–9]. More common QATBs *viz.*, tetramethyl ammonium tribromide (TMATB)[10], tetraethyl ammonium tribromide (TEATB)[11], tetrapropyl ammonium tribromide (TPATB)[12], tetrabutyl ammonium tribromide (TBATB)[13], and cetyltrimethyl ammonium tribromide (CTMATB)[14] have been synthesized by different methods over the years considering their high efficiency as brominating agent.

3.1.2. Role of the quaternary ammonium cation

As discussed in the previous chapters, QATBs consists of two ions i.e., the quaternary ammonium cation (QA^+) ion and the tribromide anion (Br_3^-) ion, which is common in every QATB and this Br_3^- is responsible for the bromination of the substrates[15,16]. However, it has been observed, despite the exclusivity of the brominating agent, there is always some variation in the reaction profile and product yield[17] which might be because of the influence of different QA^+ ion in the Br_3^- ion. The structural determination in the previous chapter clearly shows that, the QATBs have some dissimilarity in their structural geometry, which might have some influence on the reactivity of these QATBs. Therefore, it was considered important to study if the role of the quaternary ammonium cation goes beyond charge neutralization, and also it plays an active role in determining the feasibility of reactions.

3.1.3. Selected QATBs in bromination reactions

QATBs are versatile reagents and over the years their different types have been synthesized and explored various types of organic transformations and applications[1–3]. Among the various QATBs that have been studied over the years, CTMATB and TBATB have gained tremendous attention and are extensively employed in bromination of organic substrates. Despite the large number of QATBs that are present in literature, a comparative study to assess their efficiency as brominating agents is yet to be done exclusively, which is important in the pursuit of selecting a suitable reagent of choice. And thus, for the purpose of this chapter, priority have been given to only bromination reactions, where CTMATB and TBATB have been explored for their bromination efficiency through wet lab experiments and computational studies. Wet lab experiments have been performed by taking a diverse group of substrates to justify the trend in the results, where product profile analysis have been taken into account. Density functional theory (DFT) calculations have been performed taking phenol as the substrate of choice while mimicking the wet lab reaction conditions to achieve an optimum outcome. Further details of the work have been explained through this chapter.

3.1.4. Relevance of DFT studies

DFT is one of the most versatile tool in computational chemistry and there are numerous electronic parameters that can be obtained by performing a DFT calculation of chemical compounds[18–21]. Different parameters correspond to different aspects of understanding a compound or a reaction such as adsorption energy, chemical hardness, electrophilicity, transition state calculation, the energy gap of the highest occupied molecular orbital (HOMO) –lowest unoccupied molecular orbital (LUMO) etc. For this part of the study, the parameters taken into account are dissociation energy[22–24], HOMO-LUMO energy gap and dipole moment[25] of the cation. The details of the work have been presented thereof.

3.2. Materials and methods

3.2.1. Experimental studies

3.2.1.1. Bromination of organic substrates

In order to validate the findings in the literature[11,16], it was thought crucial to execute the bromination reactions under the identical reaction condition. And thus, a collection of organic substrates with different functionalities was chosen for studying the bromination reactions by CTMATB and TBATB. The substrates chosen for this study were phenol, aniline, anthracene, chalcone, o-cresol, and 1-naphthol.

For the reaction, equimolar amounts of the reagent (2 mmol) and substrate (2 mmol) were taken in a 50 ml round bottom flask and to it acetonitrile (10 ml) was added. The reaction mixture was vigorously stirred in a magnetic stirrer at room temperature. The progress of the reaction was monitored by Thin Layer Chromatography (TLC) on silica gel 60 F254 (0.25 mm). After completion of the reaction, the reaction mixture was subjected to column chromatography over a short pad of silica gel with ethyl acetate-hexane solvent system and the final product was isolated.

3.2.2. Computational studies

All the concerned structures in this work were constructed using the GaussView6[26] software and were have been optimized on the Gaussian16[27] suite of programs using the DFT employing the B3LYP hybrid functional and 6-311++G (d,p) basis set. The use of the 6-311++G(d,p) basis set has been emphasized specifically due to the quality of the basis set which is of triple-ζ quality for valence electrons with diffuse functions and thus, is suitable for structural calculations for ions and chemical species containing lone pair(s) of electrons. The equilibrium geometry optimizations were carried out without any symmetry constraints, and the optimized geometries were subjected to vibrational frequency analysis to determine the nature of stationary points and the zero-point vibration energies(ZPE)[28,29]. The absence of any imaginary frequency in the matrices of energy second derivatives (Hessian) verified the characteristic of local minima. As the wet lab experiments have been performed in acetonitrile solvent, the obtained in vacuuo geometries were subjected to further optimizations applying the Polarizable Continuum Model (PCM), with the purpose of making a proper comparison with the experimental results. In this quantum chemical approach, the solute is put in a cavity surrounding by the solvent, which is considered as a continuum defined by its dielectric constant ($\varepsilon = 37.5$ for acetonitrile)[30].

3.2.2.1. Dissociation energy

Theoretical calculations have been performed considering the well-known hypothesis that each QATB dissociates into its respective quaternary ammonium cation (QA^+) and tribromide ion (Br_3^-)[31] when exposed to certain solvent media. Therefore, it is predictable that the QATB which dissociates more quickly into its respective cation and tribromide ion is projected to the most reactive one[32]. Thus, the following equation have been treated as a reference point;

$$QATB \rightarrow QA^+ + Br_3^- \qquad (1)$$

The dissociation energies of the QATBs (in acetonitrile) were calculated as:

$\Delta E = E_{QATB} - (E_{QA^+} + E_{Br_3^-})$

Where,

ΔE= Dissociation energy of QATB

E_{QATB}= Energy of optimized QATB

E_{QA^+}= Energy of optimized QA^+

$E_{Br_3^-}$= Energy of optimized Br_3^-

It is known that higher the magnitude of ΔE (it is to be emphasized that in all the concerned cases the sign of ΔE is negative), more feasible the reaction is and accordingly more efficient is the corresponding QATB as a brominating agent.

3.2.2.2. HOMO-LUMO profiles and energy difference

The HOMO-LUMO energy gap of any molecule may be used to determine its stability and, as a result, its reactivity. Because it is energetically unfavorable to insert electrons into a high-lying LUMO and removing electrons from a low-lying HOMO, a smaller energy gap can be used as a measure of chemical and thermodynamic instability and increased chemical reactivity, and vice versa[33]. For the present study, the MO diagrams have been generated from the optimized structures using the "CubeGen" formalism present within the GaussView6 software.

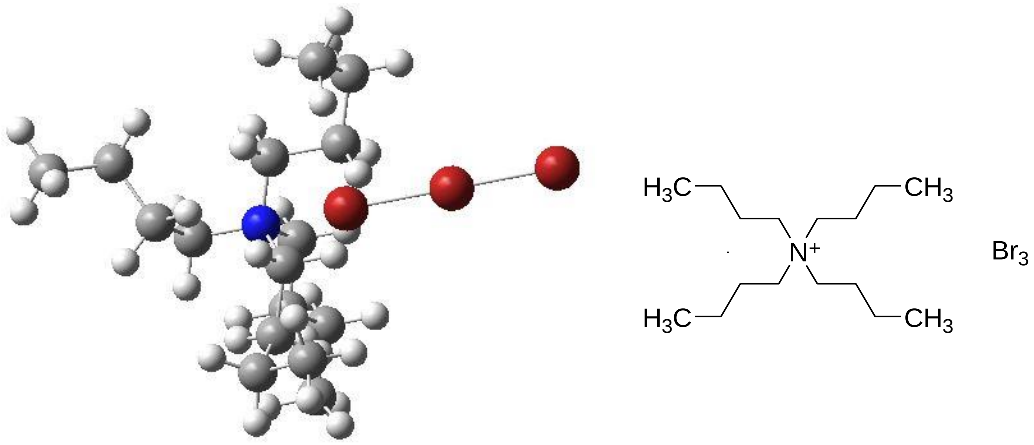
3.2.2.3. Dipole moment

The dipole moment is an important metric for determining how atoms in the same or distinct molecules interact. It is a measure of the polarity of a chemical bond within a molecule. The dipole moment of the cation has been taken into account since it is the hydration energy of the cation that will enhance the dissociation of the Br_3^- from the QATB salt into the solvent medium. Generally, a larger dipole moment corresponds to higher solvation energy which thereby would accelerate the dissociation process in a polar medium[33].

Structure of the QATBs, QA^+ and Br_3^-

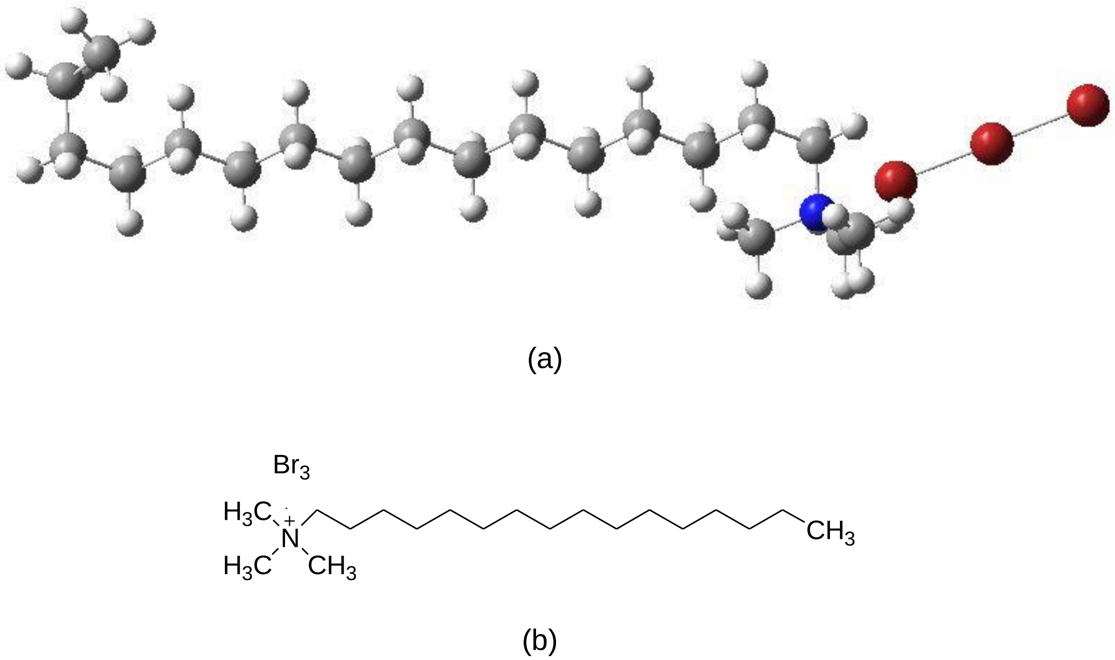
Over the years, several distinct quaternary tribromides have been synthesized, each with its own set of characteristics and reaction profiles. For the present work, emphasis have been given to bromination reactions with the aim to fully ascertain the role of the cationic part, and thus, two aliphatic quaternary ammonium tribromides, TBATB and CTMATB have been chosen for the comparison of their efficiency as brominating agents. TBATB contains four butyl groups in its cationic component, whereas CTMATB has three methyl groups and a cetyl chain in its cationic section. The structures of the TBATB, CTMATB, tetrabutyl ammonium cation (TBA^+), Cetyltrimethyl ammonium cation ($CTMA^+$), and Br_3^- obtained using the above-mentioned optimization protocol, are shown below in figure 3.1, 3.2, 3.3, 3.4, and 3.5.

Color code: O ● N ● C ● H ●



(a) (b)

Figure 3.1. (a) Optimized structure of Tetrabutyl ammonium tribromide (b) Chemical structural formula of Tetrabutyl ammonium tribromide



(a)

(b)

Figure 3.2. (a) Optimized structure of Cetyltrimethyl ammonium tribromide (b) Chemical structural formula of Cetyltrimethyl ammonium tribromide

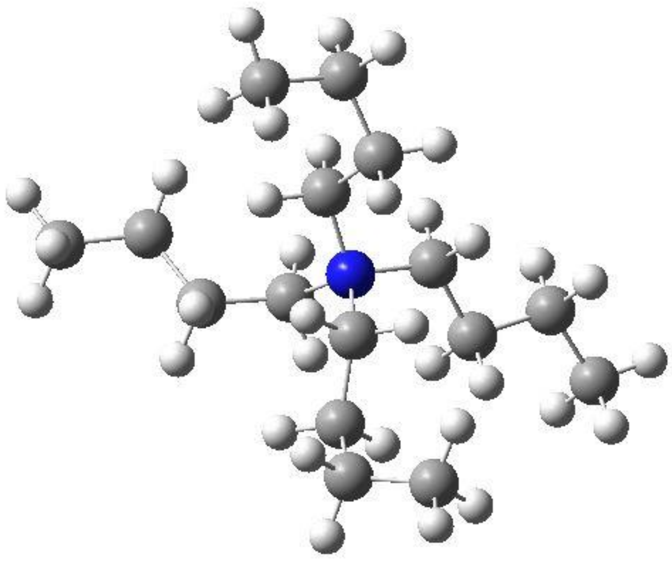


Figure 3.3. Optimized structure of Tetrabutyl ammonium ion

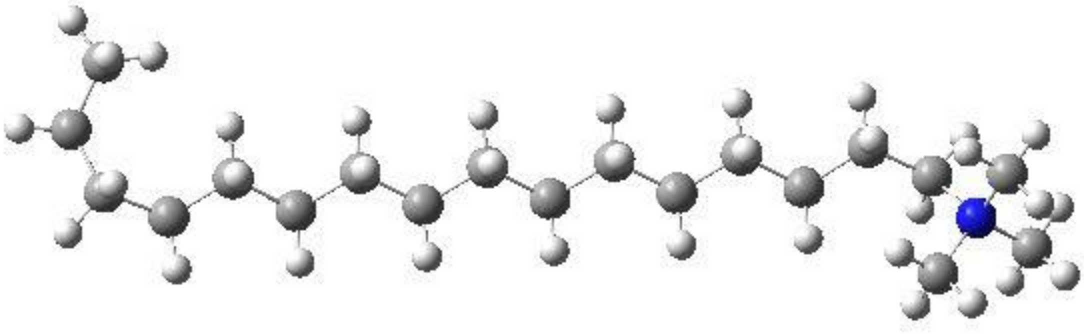


Figure 3.4. Optimized structure of Cetyltrimethyl ammonium ion

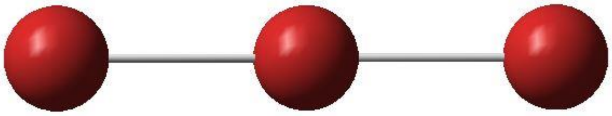


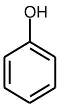
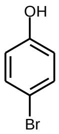
Figure 3.5. Optimized structure of Tribromide

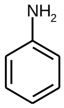
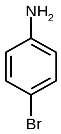
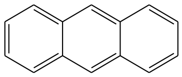
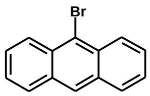
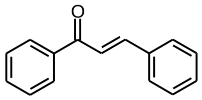
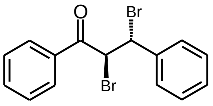
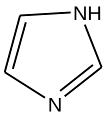
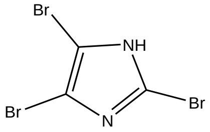
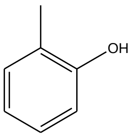
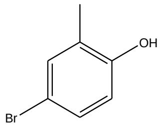
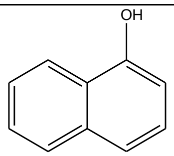
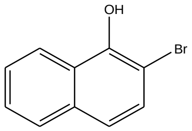
3.3. Results and discussion

3.3.1. Product profile analysis of the QATBs

In order to validate the literature reports[11,16], it was thought important to execute the bromination reactions under the same reaction conditions. Consequently, a collection of organic substrates with varied functional groups was selected for bromination reactions by TBATB and CTMATB. The details of bromination reaction profile have been shown in Table 3.1.

Table 3.1. *Bromination of organic substrates with TBATB and CTMATB in acetonitrile solvent at room temperature*

Substrate	Product[a]	Reaction time[b]		Yield[c](%)	
		TBATB	CTMATB	TBATB	CTMATB
		3h 30min	3h	60	70

		3h 10min	2h 20min	60	65
		3h 40min	3h 10min	70	87
		5h	3h 15min	65	92
		4h 20min	2h 50min	65	68
		2h 50min	2h 5min	80	82
		3h	1h 50min	81	82

[a]Products were characterized by comparison with authentic pure sample. [b]Reactions were monitored by TLC. [c]isolated yields are reported.

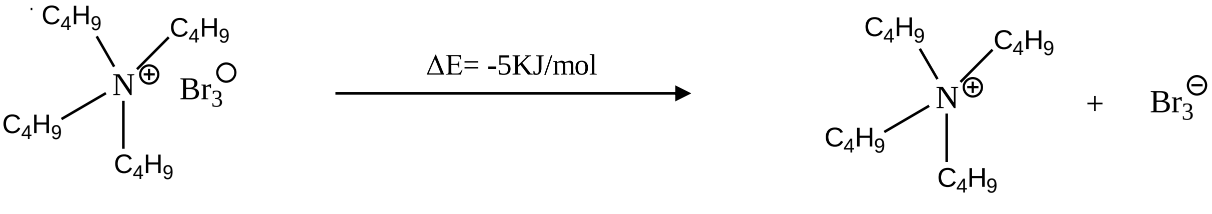
The product profile analysis of the studied reaction clearly indicated that there is no difference in product selectivity, but the reaction time and product yield is different from substrates to substrates. In case of reaction with CTMATB, the reactions tend to finish faster, giving better product yield than in the case of reaction with TBATB.

3.3.2. Reactivity parameters of the QATBs

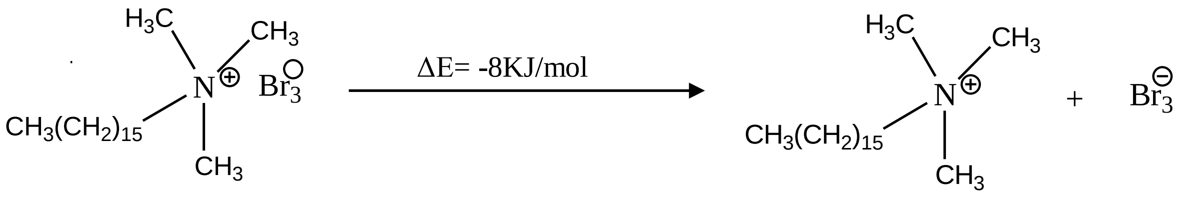
In order to support the above experimental results, dissociation energy of the two QATBs were determined using computational calculations employing the DFT method. The DFT results of dissociation energy obtained after optimizing the structures computationally are presented below in table 3.2. As can be observed from the results, the dissociation energy for TBATB is calculated to be -5 kJ/mol and that for CTMATB is -8 kJ/mol. Therefore, from the dissociation energies of the two QATBs, it can be ascertained that, in acetonitrile solvent medium, the dissociation of CTMATB is energetically more feasible than the dissociation of TBATB. Hence, it can be established that CTMATB may dissociate faster into its constituting ions and is a more efficient brominating reagent than TBATB(Scheme 3.1).

Table 3.2. *E_{QATB}, E_{QA^+}, $E_{Br_3^-}$, and ΔE of TBATB and CTMATB*

QATB	E_{QATB} (kJmol^{-1})	E_{QA^+} (kJmol^{-1})	$E_{Br_3^-}$(kJmol^{-1})	ΔE (kJmol^{-1})
TBATB	-2.2077379×10^7	-0.1801561×10^7	-2.0275813×10^7	-5
CTMATB	-2.2387140×10^7	-0.2111319×10^7		-8



TBATB TBA$^+$



CTMATB CTMA$^+$

Scheme 3.1. Schematic diagrams of dissociation of TBATB and CTMATB to give their respective cation and tribromide ion

Subsequently, the HOMO-LUMO energy gap of CTMATB and TBATB were calculated from their optimized structures and the results revealed lower HOMO-LUMO energy difference in case of CTMATB (energy gap for CTMATB is -2.54182 eV) than TBATB (energy gap for TBATB is -2.69474 eV). And as was in the previous section, a smaller HOMO-LUMO energy gap corresponds to higher reactivity of the molecule and vice versa. Therefore, it can be concluded from the results that, CTMATB will have better reactivity than TBATB in bromination of organic substrates.

Thereafter, an observation on the dipole moment of the two cations of the studied QATBs was made to determine the dissociation of $Br_3^-$from the QATB salt. As shown in table 3.3, CTMA+ has a higher dipole moment than TBA+ suggesting that the former will reinforce the dissociation of Br_3^- into solution faster than the later. Accordingly, it can be said that CTMATB will act as a better brominating agent than TBATB in polar medium.

Table 3.3. *Some molecular parameters of TBATB and CTMATB calculated using B3LYP/6-311G++(d,p) level of theory*

Parameter	TBATB	CTMATB
ΔE (kJ/mol)	-5	-8

E_{HOMO}(kJ/mol)	-739.81345	-936.96226
E_{LUMO}(kJ/mol)	-479.81345	-691.71428
$E_{[HOMO\text{-}LUMO]}$(eV)	-2.69474	-2.54182
Dipole moment(Debye)	0.7923 (TBA$^+$)	35.9861MA$^+$)

3.4. Conclusion

QATBs have always displayed different reaction profiles depending on many factors like choice of solvent, heating conditions, etc., but mostly due to the choice of QATB. In this work, two of the most popular QATBs have been chosen to study their bromination efficiency through experimental as well as computational calculations. Accordingly, the effect of their cations on the bromination reactions have been studied by performing reactions with a group of substrates consisting of different functionalities. Thereafter, DFT calculations were performed to determine the dissociation energy and HOMO-LUMO energy gap of the molecules as well as the dipole moment of their respective cations. The wet lab experiments indicated that CTMATB has an edge over TBATB in terms of reaction time and product yield. Thereafter, the results of the dissociation energy displayed that the dissociation of CTMATB to CTMA+ and Br$_3^-$ should be more feasible than the dissociation of TBATB to its constituent ions. Subsequently, it was found that the HOMO-LUMO energy of CTMATB is smaller than that of TBATB, further justifying the better reactivity of CTMATB. Lastly, the dipole moments of CTMA+ and TBA+ were observed to determine the dissociation efficiency of the respective QATBs to give Br$_3^-$ and the results once again indicated towards the better dissociation of CTMATB as compared to that of TBATB. And thus, it can be said that the results of all the experiments and calculations in this work suggested towards the better reactivity of CTMATB over TBATB thereby proving that the experimental and computational studies complimenting each other. This work is conducted with the expectation of building a foundation to highlight better brominating agents for the purpose of achieving a maximum outcome from any bromination reaction.

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Chapter 4

a) Study on the Efficiencies of CTMATB and TBATB in Bromination of Activated Carbon

Brominated activated carbon is an extremely important material especially in mercury removal. Brominated activated carbon is usually prepared by bromination of the activated carbon surface with liquid bromine, which is well-known for its high toxicity. However, efforts are being made to find more environmentally benign brominating reagents, for preparing brominated activated carbons. Therefore, in this piece of work, TBATB and CTMATB have been explored to compare their potentials as brominating agents in bromination of activated carbon.

4.1. Introduction

4.1.1. Importance of brominated activated carbon

The usefulness of activated carbon (AC) has been widely reported with applications such as water and air purification[1,2], use in cosmetic industry[3], is used for methane and hydrogen storage[4,5], etc. Due to their wide range of applications, various researchers over the world have been attempting to make modifications in the AC surface in order to enhance its properties. One such modification leads to the production of brominated activated carbon (BAC) which have shown tremendous enhancement of properties over pristine AC in terms of pollutant removal, electrochemical properties, etc[6].

4.1.2. Common brominating agents for preparation of BAC

Bromine is known to be the most common brominating agent for preparation of brominated compounds[7,8]. And the same is the case for brominated activated carbon (BAC) which as per literature review, is prepared mostly by using bromine considering the spontaneous bromination of the substrates. For example, Papirer *et al.* 1994 did an XPS study where they used bromine vapours in CCl_4 solvent medium for bromination of carbon black[9]. Jin *et al.* 2000 studied the intercalation of bromine in multi-wall carbon nano tubes where liquid bromine was used for the purpose under N_2[10]. Barpanda *et al.* 2011[6] reported the preparation of BAC using liquid bromine to study the structure, surface morphology and electrochemical properties of the prepared compound. Further, Bulusheva *et al.* 2012[11], Friedrich *et al.* 2013[12], and Jankovsky *et al.* 2014[13] reported the application of bromine for bromination of their respective carbon materials. It is quite clear that bromine has been extensively used for bromination of different kinds of carbon materials. However, despite its efficiency, the toxicity related to the same cannot be neglected and thus continuous attempts are being made by researchers to find and use environmentally benign alternative agents for preparation of BAC. Among the various available alternatives, Cetyltrimethyl ammonium tribromide (CTMATB) has also been explored for the bromination of activated carbons (ACs), and thereby the BAC prepared have been successfully applied for the removal of bacteria from water[14]. Although the efficiency of CTMATB is well established, it has some limitations because of its bulky size and surfactant properties. CTMATB is just one type of quaternary ammonium tribromide (QATB) and there are various others with different cationic parts, among which, tetrabutyl ammonium tribromide (TBATB)[15] is also a popular reagent. With an attempt to introduce a new brominating agent for synthesis of brominated activated carbon (BAC), in this work the efficiencies of CTMATB and TBATB in bromination of ACs have been compared.

4.1.3. Effects of surface functional groups in preparation of BAC

A factor that affects the efficiency of bromination of activated carbon is the presence of surface functional groups[16]. The nature of the functional groups depends on the activation process of the carbon[17,18]. Among the various activation processes, KOH activation is one of the most common methods which leads to formation of oxygen containing functional groups on the activated carbon (AC) surface[19–21]. Therefore, in this study certain oxygen containing functional groups have been considered to explore their effects on the AC surface and to determine the brominating efficiency of CTMATB and TBATB for bromination of the studied activated carbon models. Density functional theory (DFT) has been used for determining various parameters which defines the reactivity of any compound.

4.2. Materials and methods

Computational calculations come with their own set of requirements, such as, it is extremely important to construct the structures with exact accuracy, to apply the appropriate method, embedding the right solvent conditions, observing the vibrational frequencies, etc. And therefore, an extensive literature review was conducted before performing the calculations computationally so as to maximize the precision in results. For this work, Gaussian16[22] software was used for the optimization of all the concerned structures which were initially constructed in the GaussView6[23] graphical user interface. The structures were optimized at B3LYP[24] model of theory with 6-31G basis set[25]. These reactions are usually performed in water and thus the polarizable continuum method was fitted with dielectric constant of $\varepsilon = 78.4$[26] to introduce the solvent conditions of water. Additionally, vibrational frequency analysis was also observed to validate the nature of stationary points.

The parameters studied for this piece of work are:

4.2.1. Interaction energy

The interaction energy of various interaction between TBATB and the ACs have been determined to observe the best interaction between them.

4.2.2. Bond lengths

Various bond lengths have been evaluated to determine the best interaction and the bond strengths of various bonds.

4.2.3. Relative total energy

Relative total energy was evaluated to study the most favoured position for bromination the studied ACs surface.

For understanding any interaction theoretically, it is vital to construct and use the correct models of structure. According to the solid-state ^{13}C nuclear magnetic resonance observations, there are three to seven fused rings in the activated carbon surface[27]. A four benzene rings ($C_{16}H_6$) armchair model was chosen for the present study where the upper edge side was unsaturated of hydrogen atoms to generate the active sites for bromination. Since KOH activation is one of the most common methods for activation of carbon, the oxygen containing functional groups have been chosen for this study and thus the groups have been embedded in the active sites of the activated carbon surface for studying their interaction with TBATB/CTMATB. The oxygen containing functional groups such as hydroxyl (OH), carboxyl (COOH), and aldehyde (CHO) are introduced in the activated carbon surface to determine their influence on the extent of bromination/interaction. The AC models were named pristine armchair (AC-P), -OH armchair (AC-OH), -COOH armchair (AC-COOH), -CHO armchair (AC-CHO), and -COOH+CHO+OH armchair (AC-ALL) is presented in the figure 4.1 below.

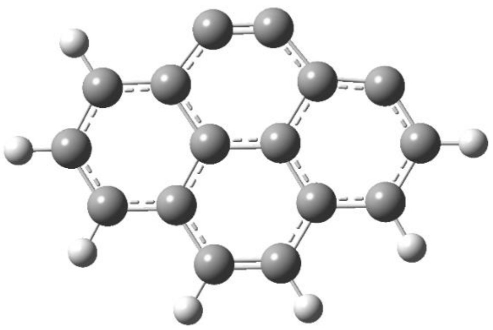
The interaction energy (E_I) of the TBATB/CTMATB and activated carbon is calculated using equation

$$E_I = E_{AB} - (E_A + E_B)$$

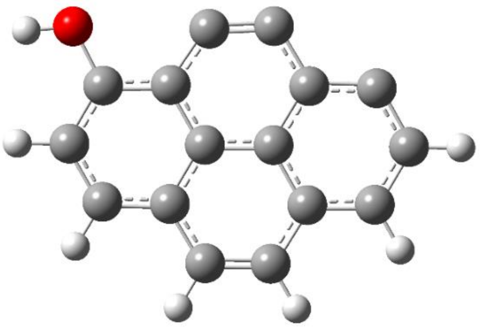
where, E_{AB} is the total energy of TBATB/CTMATB and activated carbon in an equilibrium state; $E_A$is the total energy of the TBATB/CTMATB; E_B is the total energy of the activated carbon. Generally, the higher negative value of interaction energy indicates more stability and stronger interaction.

Following that, it is expected that in case of QATBs, Br_2 is released during bromination, which happens when there is bond lengthening of one Br-Br and bond shortening of another Br-Br in the Br_3^- species. The bond lengthening usually occurs between the Br atom closest to the N atom of the quaternary ammonium cation in QATBs and the central Br atom of Br_3^-, while the bond shortening happens between the central Br atom and terminal Br atom in Br_3^-. In the present study, in the structures of CTMATB and TBATB, the Br atom nearest to the N atom is designated as Br1, the central Br atom is considered as Br2 and the Br atom farthest away from the N atom as Br3. Thus, the bond lengths Br1-Br2 and Br2-Br3 are observed in CTMATB and TBATB in the presence of all the activated carbon models under study so as to determine how they influence the Br-Br bonds in these QATBs. An efficient interaction will be one in which the Br1-Br2 bond length is longest and Br2-Br3 bond length is shortest, thus a fourth parameter is studied where the ratio of Br1-Br2 and Br2-Br3 is determined in order to see if which interaction have the highest efficiency to brominate the activated carbon.

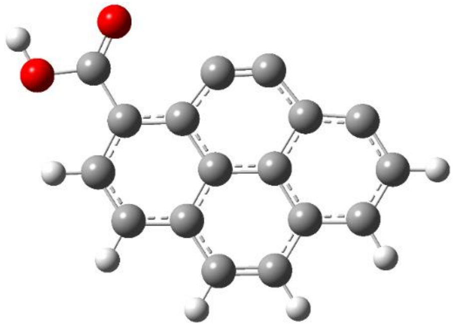
Subsequently, it was considered important to determine the most stable configuration of each brominated activated carbon (BAC) i.e., the most stable position for the bromine attachment in each activated carbon (AC). For this purpose, the total energies of all possible configurations of all the studies compounds have been evaluated and compared. The structures with the least energies among all possible configurations of each compound have been chosen as the accepted bromine attachment position. And lastly, the C-Br bond length has also been observed to determine the strongest C-Br bonded structures.



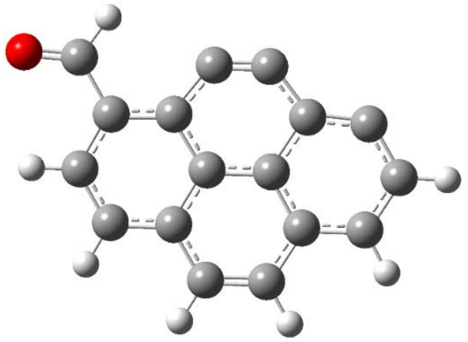
AC-P



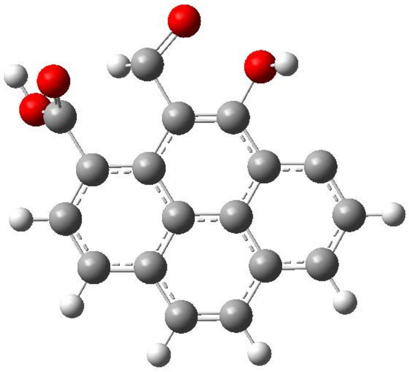
AC-OH



AC-COOH



AC-CHO



AC-ALL

Color key: ● ● ●

C H O

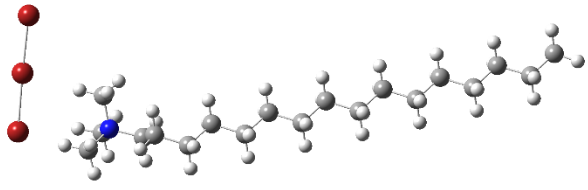
Figure 4.1. Optimized structures of pristine and functionalised activated carbon

4.3. Results and discussion

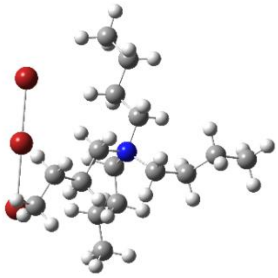
Brominated activated carbon serves as a vital industrial component. However, due to the adverse effects of bromine, alternate brominating agents are frequently explored. QATBs have garnered reputation as excellent reagents for bromination of various groups of organic substrates and thus in this study an attempt has been made to study the interaction of two of the most popular QATBs viz. CTMATB and TBATB with pristine and functionalized activated carbon.

4.3.1. Determining the best interaction between different ACs and the two QATBs

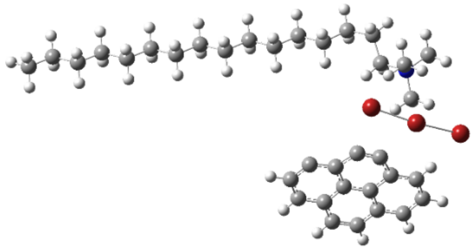
For this study, hydroxyl (-OH), carboxyl (-COOH), aldehyde (-CHO) functional groups were chosen and accordingly, five carbon models depicting AC-P, AC-OH, AC-COOH, AC-CHO, and AC-ALL were considered and their interactions with CTMATB and TBATB was studied. The consideration of activated carbon models with different functional group would aid in understanding the effect of such functionalities on the extent of activated carbon bromination. The various interactions representing the bromination process are given in figure 4.2, while the interaction energies and the bond length obtained for the various type of bromination interactions are given in table 4.1.



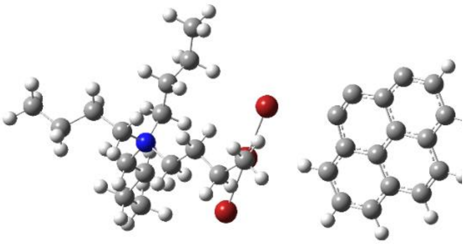
CTMATB



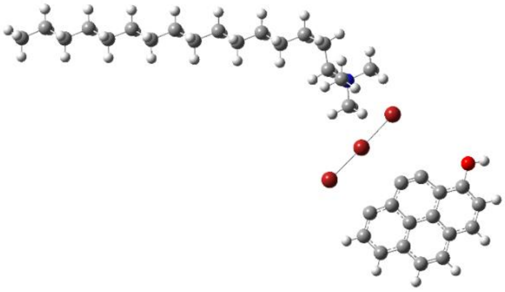
TBATB



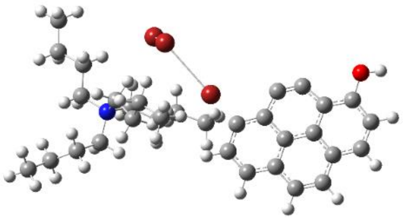
AC-P+CTMATB



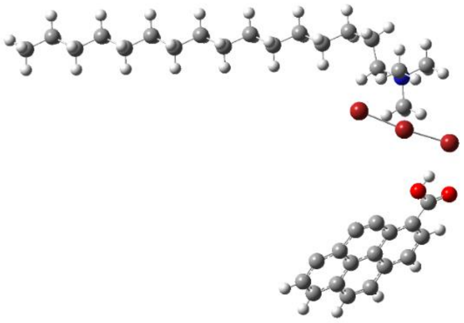
AC-P+TBATB



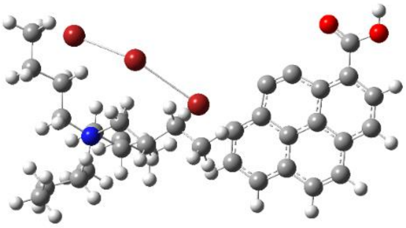
AC-OH+CTMATB



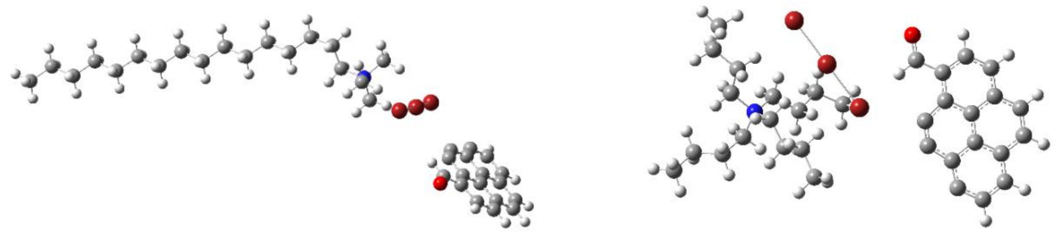
AC-OH+TBATB



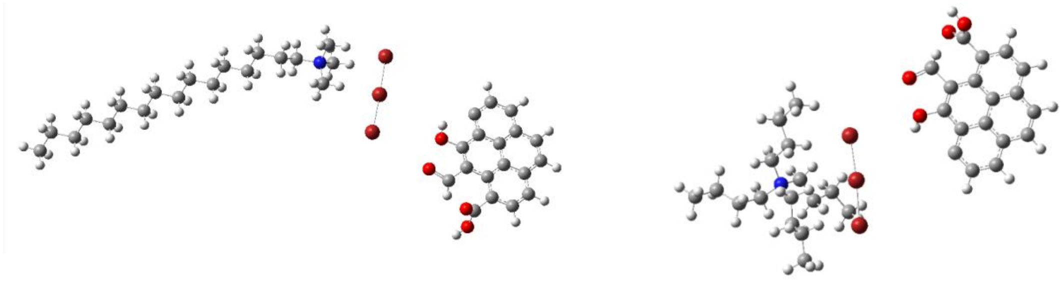
AC-COOH+CTMATB



AC-COOH+TBATB



AC-CHO+CTMATB AC-CHO+TBATB



AC-ALL+ CTMATB AC-ALL+TBATB

Figure 4.2. Various interactions depicting the bromination process

Color key: ● C ● H ● O ● Br ● N

Table 4.1. *The interaction energies and the bond lengths obtained for the various type of bromination interactions*

QATB	AC model	Interaction energy (kJ/mol)	Br1-Br2 bond length (Å)	Br2-Br3 bond length (Å)	Br1-Br2/Br2-Br3
CTMATB	---	---	2.71	2.68	1.01
	AC-P	-16.12	2.69	2.67	1.01
	AC-OH	-9.53	2.70	2.68	1.01
	AC-COOH	-17.37	2.72	2.66	1.02
	AC-CHO	-7.48	2.72	2.68	1.01
	AC-ALL	-13.04	2.69	2.67	1.01
TBATB	---	---	2.70	2.69	1.00
	AC-P	-17.61	2.69	2.68	1.00

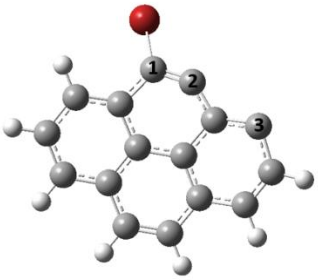
	AC-OH	-102.59	3.33	2.96	1.13
	AC-COOH	-194.31	3.38	2.95	1.15
	AC-CHO	-12.48	2.70	2.69	1.00
	AC-ALL	-54.62	2.47	2.46	1.00

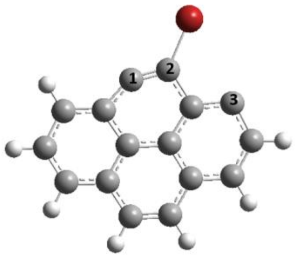
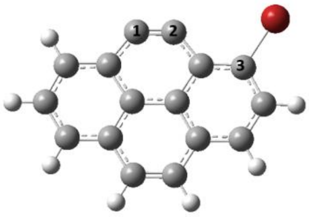
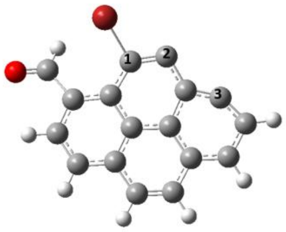
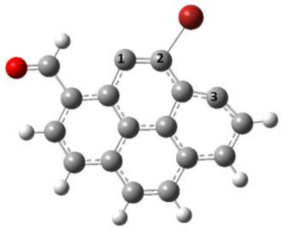
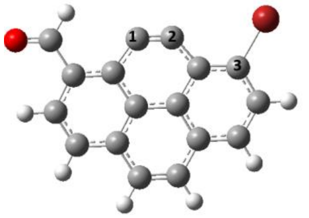
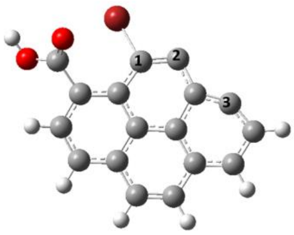
From the table, it can be inferred that functionalized activated carbon might have better interaction with CTMATB and TBATB than pristine activated carbon. Additionally, it can be observed that in general the modelled ACs have better interaction with TBATB as compared to CTMATB. Furthermore, the interaction energy is lowest in case of interaction with AC-COOH for both CTMATB and TBATB (-17.37 kJ/mol for AC-COOH+CTMATB and -194.31 kJ/mol for AC-COOH+TBATB). Also, the strongest interaction was observed in case of AC-COOH+TBATB (-194.31 kJ/mol) which has the lowest energy among all the studied interactions. Thereafter, when we observe the various bond lengths, it becomes clear that the results of interaction energy compliment with the bond length ratio. The interactions with lower energy have a higher Br1-Br2/Br2-Br3 ratio indicating that during these interactions the release of Br_2 will be faster. The ratio is highest again for interaction with AC-COOH for both CTMATB and TBATB (1.02 for AC-COOH+CTMATB and 1.15 for AC-COOH+TBATB). Further, the results, it can be understood that the ratio is highest for AC-COOH+TBATB (1.15 for AC-COOH+TBATB). Therefore, from the table, it can be said that TBATB might act as a better brominating agent for bromination of activated carbon than CTMATB. Also, the presence of COOH functional group on the AC surface might positively influence the interaction of the ACs with the QATBs.

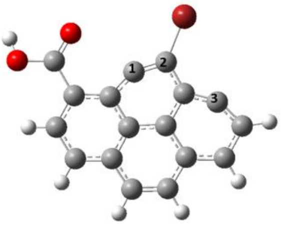
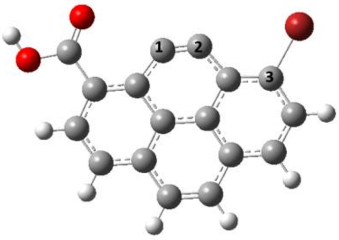
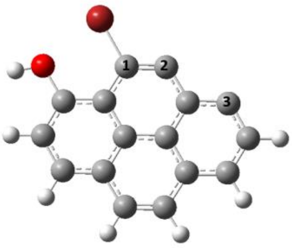
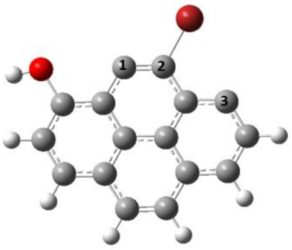
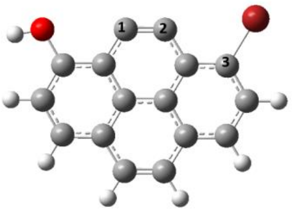
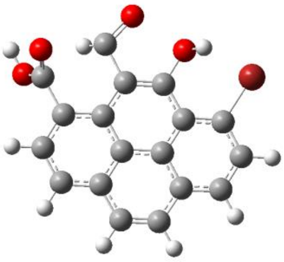
4.3.2. Determining the most favourable position for bromination in the AC surface

Thereafter, effort was made towards obtaining the most preferred bromine attached configuration by determining the total energies of all possible systems and the C-Br bond length in each case. There are three positions of carbon possible for bromination in each activated carbon (AC) except for AC-ALL where all the three functional groups are embedded. The three carbons in each AC have been numbered as 1, 2, and 3 as shown in the figures in table 4.2. As per well-established fact, the configuration with the lowest energy (highest negative value) will be the most stable structure and a shorter C-Br bond represents strong bonding in the compound. The results of this assessment are presented in table 4.2 as given below. In order to maintain simplicity in the results obtained, the total energies are converted into kJ/mol and the relative energies are presented where the highest energy in each case is considered as 0.

Table 4.2. *Total energies of all the bromine containing systems*

Functional groups	Possible bromine positions	Relative total energy (in kJ/mol)	C-Br bond length (Å)
Pristine BAC			
No functional groups		-59.17	1.93

		0	1.94
		-371.36	1.89
Oxygen group functionalized BAC			
-CHO		0	1.99
		-45.16	1.99
		-313.65	1.94
-COOH		0	1.98

		-274.49	1.94
		-377.96	1.92
-OH		0	1.98
		-21.35	2.00
		-356.85	1.94
-COOH+CHO+OH		0	1.97

The results obtained in table 4.2. clearly indicate that the most preferred position for bromination is at carbon number 3 in all the cases. The relative total energy is the lowest (highest negative value) in the structures with bromine in the third position. Further, the C-Br bond length also indicates that position 3 is most favourable as the strongest bonds are all in position 3. Therefore, from these results, we can conclude that bromination might occur in position 3 all the cases.

4.4. Conclusion

This study was conducted to explore the potential of QATBs in bromination of AC and therefore CTMATB and TBATB were chosen as representatives for QATBs and few AC models were chosen including pristine AC and some oxygenated functionals containing ACs like AC-OH, AC-COOH, AC-CHO, and AC-ALL to understand their interaction. The first part of the study was to evaluate the influence of the surface functionals on the interaction of the ACs with the QATBs, and the results revealed that TBATB might be a better brominating agent than CTMATB for bromination of the studied ACs and that the COOH functional might have a better influence in the interaction of the ACs with both the QATBs. Thereafter, an effort was made to determine the most favourable position for bromination on the engaged ACs surfaces and the results indicated that position 3 is most favourable as the relative energies are lowest when bromine is attached in this position and the strongest bonds are all in position 3 as indicated pictorially in the images above.

4.5. References

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Chapter 4

b) Determining the Influence of Oxygenated Functionals on Brominated Activated Carbon towards Mercury Adsorption

Mercury toxicity has been widely reported; therefore, newer methods are continuously being designed to remove mercury from water and air. Brominated activated carbon is an excellent candidate for mercury removal through surface adsorption, which has been used in various ways to adsorb mercury efficiently. Different types of brominated activated carbons have been prepared and studied for their mercury adsorption ability; however, the effect of oxygenated functionals on the mercury adsorption ability of brominated activated carbons has not been explored exclusively. Therefore, this chapter presents the efficiencies of certain oxygenated functionals containing brominated activated carbon, designed in the previous part of this chapter, in mercury adsorption.

4.6. Introduction

4.6.1. Hazards associated with mercury

Mercury is a highly hazardous heavy metal which is harmful to plant as well as animal life due to its extreme toxicity, transport through food chain and bio accumulation[1,2]. Mercury is released into the atmosphere from various sources like oil refining, cement production, biomass burning etc. and natural sources like volcanic eruption, geothermal springs, emission from the ocean etc[3,4]. One of the major sources of anthropogenic mercury pollution is coal-fired power plants accounting for almost 30% of mercury emissions into the atmosphere[5].

4.6.2. Different processes for mercury removal

There are mainly three forms of mercury in the flue gas which are elemental mercury (Hg^0), oxidised mercury (Hg^{2+}), and particulate-bound mercury (Hg^p)[6]. Among these, the Hg^0 is most difficult to remove which is because of its high vapour pressure, high operating temperatures, and low solubility in water[7]. Zambrano *et al.*, 2002 reported the removal of mercury from aqueous solutions by the method of complexation-ultrafiltration[8]. Abai *et al.*, 2015 reported the removal of mercury from natural gas using ionic liquids[9]. Then, Liu *et al.*, 2020 reported the removal from mercury from coal-fired flue gas using mineral adsorbents[10]. Again, Altaf *et al.*, 2022 reported the removal of elemental mercury (Hg^0) from coal syngas by using magnetic tea-biochar[11]. Wu *et al.*, 2022 reported the gas phase removal of elemental mercury using rod-like Bi_2S_3 single crystals[12]. Zeng *et al.*, 2022 studied the adsorption of mercury ions from aqueous solutions using high-performance Zn-based coordination polymers[13].

4.6.3. Role of BACs in mercury removal

One of the most efficient ways of capturing the Hg^0 is using brominated activated carbon (BAC) as have been reported vastly in literature and the modification is still ongoing[14,15]. Hutson *et al.,* 2007, reported the XAS and XPS characterization of mercury binding onto activated carbon to determine the mode the binding on the BAC surface[16]. Zhao *et. al.,* 2021, studied the mercury removal efficiency of brominated rice husk activated carbon and compared with commercially available brominated coal based activated carbon[15]. There are also many density functional theory (DFT) studies on the application of BAC in mercury removal viz., Geng *et al.,* 2022, reported a DFT study of the mechanochemical bromination of unburnt carbon in fly ash and thereby determined its efficiency in mercury removal[17].

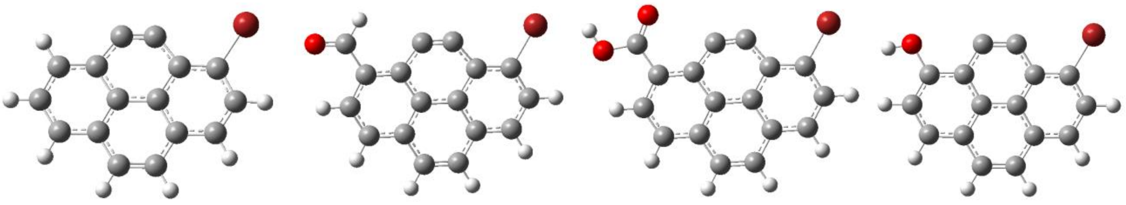
The activation process of carbon usually leads to attachment of functionals groups on the activated carbon (AC) surface which influence the efficiencies of the AC in different applications[18]. One such set of functional groups are the oxygen containing functional groups as -OH, -COOH etc which arises from KOH activation of the carbon material[19]. The presence of these functional groups has been reported to enhance the activity of the activated carbon and have showed better performance than pristine activated carbon in various pollutant removal studies[15]. Therefore, it is possible that the presence of these groups in the surface of BAC might also improve their properties in mercury removal. There are a few reports of oxygenated functionals containing brominated activated carbon (OBAC) in mercury removal[20,21], however no exclusive reports on the efficiencies of different OBACs in mercury adsorption. Therefore, through this piece of work, an effort has been made to understand the influence of certain oxygenated functionals on the mercury adsorption ability of BAC.

Subsequently, considering mercury removal is an ongoing research and newer materials are developed frequently with the aim of producing better materials than the existing ones, the OBAC models and the pristine BAC model designed computationally in the previous chapter have been employed for testing their mercury adsorption abilities. Electronic parameters such as adsorption energy, total energy, and bond lengths were evaluated to rationalize the results. Through this work, the importance of oxygenated functionals for efficient removal of mercury was explained.

4.7. Materials and methods

Gaussian16[22] suite of programme has been used as the prime software for the energy minimization of all the structures which were constructed and viewed in the GaussView6[23] graphical user interface. Along with geometry optimization, vibrational frequency analysis was also performed to ensure the nature of stationary points. B3LYP/LANL2DZ[24] level was theory was employed along with the polarizable continuum model of water to create the solvation condition of water (ε=78.4).

The OBAC models and the pristine BAC model designed in the previous chapter are considered for understanding their ability in mercury adsorption and the structures are shown below in figure 4.3.



(a) (b) (c) (d)

Figure 4.3. Designed models of (a) pristine BAC (b) -CHO BAC (c) -COOH BAC (d) -OH BAC

Color key: ● ● ● ●
C H O Br

The parameters evaluated for this study are:

4.7.1. Adsorption energy

The adsorption energy of various adsorption between mercury and the BACs have been determined to observe the best adsorption between them.

4.7.2. Bond lengths

Various bond lengths have been evaluated to determine the best adsorption and the bond strengths of various bonds.

4.7.3. Relative total energy

Relative total energy was evaluated to study the most favoured position for the adsorption of mercury on the studied BACs surface.

Subsequently, the adsorption energies for the adsorption of mercury in each OBAC and pristine BAC have been evaluated employing the formula given below:

$E_{ads} = E_{BAC+Hg} – (E_{BAC} + E_{Hg})$

Where, E_{ads} = mercury adsorption energy of the respective BAC, E_{BAC+Hg} = total energy of respective BAC and mercury system, E_{BAC} = total energy of the respective BAC, E_{Hg} = total energy of mercury. Literature suggests that an adsorption energy of less than -30 kJ/mol suggests physisorption and more than -50 kJ/mol indicates chemisorption. A lower value of adsorption energy corresponds to a stronger adsorption.

Along with the adsorption energy, the relative total energies of the possible positions where Hg can be adsorbed was determined in order to select the most favourable position for the adsorption. Subsequently, the C-Hg or Br-Hg bond lengths in all the positions for all the engaged structures were evaluated to determine the strongest bond.

4.8. Results and discussion

The OBAC models designed in the previous chapter have been employed for understanding their mercury adsorption ability. Various electrochemical parameters like adsorption energy, total relative energy, and bond lengths have been evaluated for some positions where mercury might possibly adsorb, to determine the influence of the oxygenated functionals on the mercury adsorption abilities of the studied OBACs. Further, the most favourable position for mercury adsorption was also determined. The results of all the calculations are presented in table 4.3 below. In order to understand the efficiencies of the modelled OBAC, pristine BAC has also been considered for comparison. The adsorption energies of all the structures for adsorption of mercury were calculated and further, the relative total energies and the C-Hg and Br-Hg bond lengths were analysed to determine the most favoured position for the adsorption of mercury.

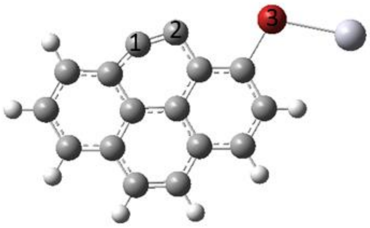
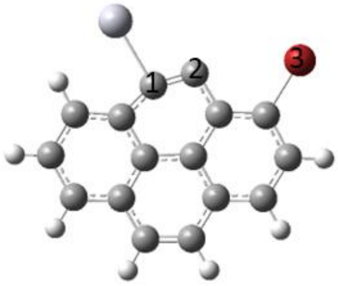
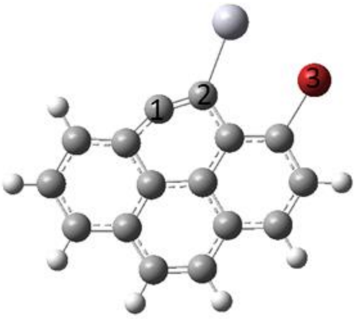
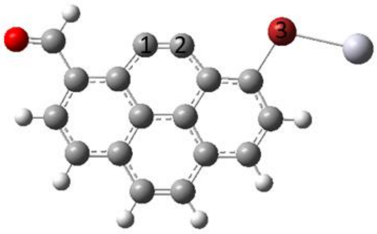
4.8.1. Determining the BAC with the strongest mercury adsorption ability

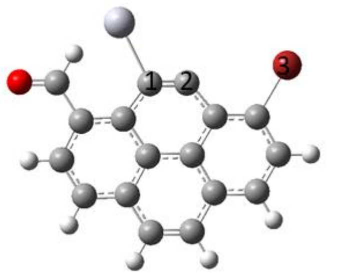
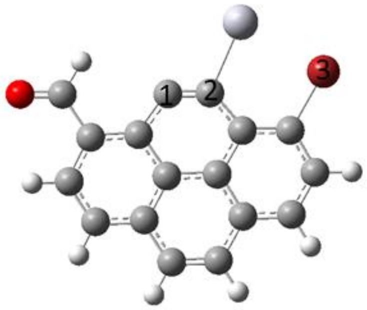
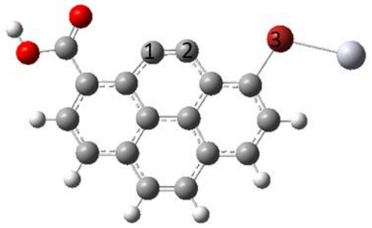
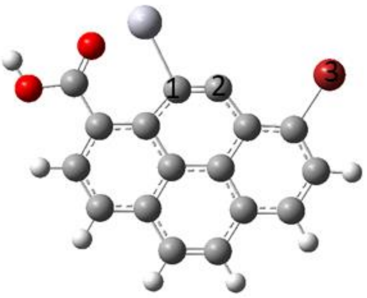
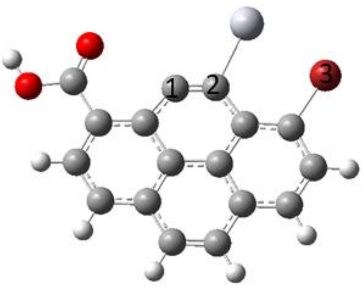
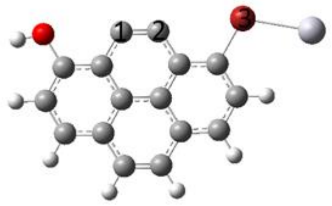
From the results of the adsorption energy, relative total energy, and C-Hg/Br-Hg bond lengths, it can be observed that -COOH might have a better influence on the mercury adsorption ability of the designed OBACs. The adsorption energy is lowest in case of -COOH i.e., -1.4475 kJ/mol, at carbon position 1 as marked in the structures. The relative total energy is also lowest for -COOH at carbon position 1, and the C-Hg bond length is also strongest at the same position for -COOH. Thus, from the results it can be inferred that -COOH functional on the BAC surface might enhance the mercury adsorption ability of the BAC as compared to pristine BAC and -CHO and -OH BACs as adsorption energy and the relative total energies are lowest in case of -COOH and also the C-Hg bond is strongest in the presence of -COOH group. The conclusion that the presence of the -COOH group on the surface of the BAC might have a better influence than the other studied functionals is in agreement with various reports as documented in literature.

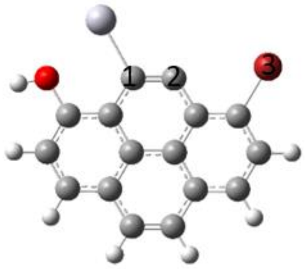
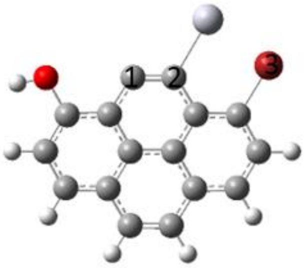
4.8.2. Determining the most favourable position for mercury adsorption

From the results it was found that for all the studied models, carbon position 1 might be most favourable for mercury adsorption. This is because, for all the structures, the adsorption energies, the relative total energies are lowest and the C-Hg bond length is strongest at this position, suggesting a stronger adsorption.

Table 4.3. *Total energies of all the mercury containing systems*

<table>
<tr><th>Functional groups</th><th>Possible positions for mercury adsorption</th><th>Adsorption energy (in kJ/mol)</th><th>Relative total energy (in kJ/mol)</th><th>C-Hg or Br-Hg bond length (Å)</th></tr>
<tr><td colspan="5">Pristine BAC</td></tr>
<tr><td rowspan="3">No functional groups</td><td>
</td><td>-0.30</td><td>0</td><td>5.02</td></tr>
<tr><td>
</td><td>-0.49</td><td>-0.42</td><td>4.85</td></tr>
<tr><td>
</td><td>-0.23</td><td>-0.19</td><td>5.04</td></tr>
<tr><td colspan="5">OBAC</td></tr>
<tr><td>-CHO</td><td>
</td><td>-0.46</td><td>0</td><td>5.31</td></tr>
</table>

		-0.52	-0.068	5.20
		-0.52	-0.065	5.54
-COOH		-0.49	0	5.25
		-1.45	-0.94	4.57
		-1.42	-0.93	5.25
		-0.51	0	5.20

-OH		-1.05	-0.54	4.72
		-0.83	-0.32	4.96
Color key: ● ● ● ● ● C H O Br Hg				

4.9. Conclusion

In this work, an effort was made to introduce new materials for the adsorption of mercury. For the initial part, few oxygenated functionals containing BAC models as designed in the previous part of this chapter were studied for their potentials in the adsorption of mercury. After determining the adsorption energy, relative total energy, and the C-Hg/Br-Hg bond lengths, it was observed that among the studied materials, the presence of -COOH group in the BAC surface will have better influence in the adsorption of mercury than the other oxygenated functionals. Further, mercury adsorption might possibly take place on the carbon 1 of the OBAC surface as indicated in the structures above. This work is expected to introduce new materials for removal of mercury.

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Chapter 5

Deducing the Mechanistic Pathway of Aromatic Bromination by Quaternary Ammonium Tribromides

The reaction mechanism of any reaction is a vital component for optimizing reaction condition. Therefore, considering the importance of QATBs, in this chapter, an effort is made to understand the mechanistic pathway of bromination by QATBs, taking phenol and nitrobenzene as test substrates.

A part of this chapter has been published in:

Journal of the Indian Chemical Society, **2022,** Volume 99, Issue 8.

5.1. Introduction

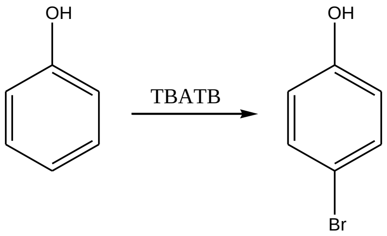
5.1.1. Importance of understanding the bromination reaction mechanism of QATBs

Bromination reactions is one of the most important organic transformations in chemistry considering the importance of bromo-organic compounds[1]. Among the various brominating agents, molecular bromine (Br_2) was most commonly used for these transformations before its toxicity was acknowledged[2]. However, as green chemistry has progressed, there has been a greater emphasis on avoiding the usage of harmful chemicals[3], and this is how quaternary ammonium tribromides (QATBs) became popular as environmentally benign alternatives to bromine. Even though the versatility and efficiency of QATBs have been well discussed in the previous chapters, till date it has not been possible to prove the mechanism through which QATBs promote bromination. It is vital to know the bromination reaction mechanism by QATBs as it will allow researchers to modify the reaction conditions to develop a more efficient and greener reaction process. Knowledge of the mechanistic pathway also provides information about the transition states and intermediates which might be useful to as they might have their own properties which might not be observed in the starting materials or products[4,5].

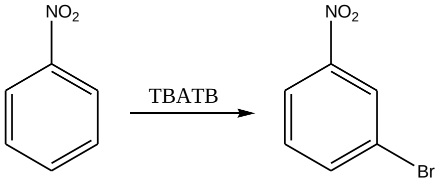
5.1.2. Existing reports on attempts to comprehend the mechanistic pathway of bromination by QATBs

In these compounds, while the cationic part can be of varied types, it is the anionic component, i.e., a tribromide ion (Br_3^-) which is the active reagent. The existing reports indicates that Br_3^- dissociates into Br^- to Br_2 during the course of a bromination reaction after which the Br_2 brominates the substrates under study[6–8], however, experimental evidence does not seem to be available to support this assertion. UV studies suggest that Br_3^- is the reactive species for bromination and there was no absorption peak for Br_2 during the course of the reaction, which can be because of a spontaneous reaction[9]. Because of these ascertains, there is always a confusion about the exact mechanistic pathway of bromination by QATBs.

Our group have been working on different aspects of QATBs[10–15] and the inability to identify or construct a correct experimental approach to verify the mechanism for bromination reactions prompted us to explore the subject using computational simulations specifically employing density functional theory (DFT)[16–19]. Aromatic bromination using QATBs have been reported widely in literature because of the importance of bromo aromatic compounds, and therefore, we considered it worthwhile to first establish the mechanism for the bromination of aromatic systems. Accordingly, in this piece of work, an attempt is made to develop the mechanism of bromination of an activated and a deactivated aromatic ring, taking phenol and nitrobenzene as test substrates and tetrabutyl ammonium tribromide (TBATB) was chosen as the representative of the QATBs. The schemes for bromination of phenol and nitrobenzene by TBATB is shown below in scheme 5.1 and 5.2 respectively[20–23].



Scheme 5.1. Bromination of phenol by TBATB[20–22]



Scheme 5.2. Bromination of nitrobenzene by TBATB[23]

5.2. Materials and methods

GaussView6[24] serves as an extremely versatile tool for building chemical structures of all types and it also allows one to specify important electronic parameters based on experimental requirement. All the concerned structures in this work have been built in the GaussView6 graphical user interface for optimization which is also used for viewing and analysing the structures after optimization. Gaussian16[25] suite of program was used for optimization of all the structures which were then subjected to vibrational frequency analysis[26,27] in order to determine the nature of stationary points. Since QATBs act as efficient brominating agents under various reaction conditions, no implicit solvent medium was employed for the optimization of the structures.

The reactivity parameters studied for this work are:

5.2.1. Bond length

Different bond lengths have been observed to determine the changes in the structure of TBATB in the presence of substrates.

5.2.2. Atomic charges using different schemes

Different schemes have been employed to determine atomic charges to justify the trend in results.

5.2.3. Relative total energies from transition state calculation

Transition state (TS) calculations were performed and the relative total energies of all the involved structures were recorded to determine the mechanistic pathway of bromination.

Optimization of Br_2 and Br_3^- structures

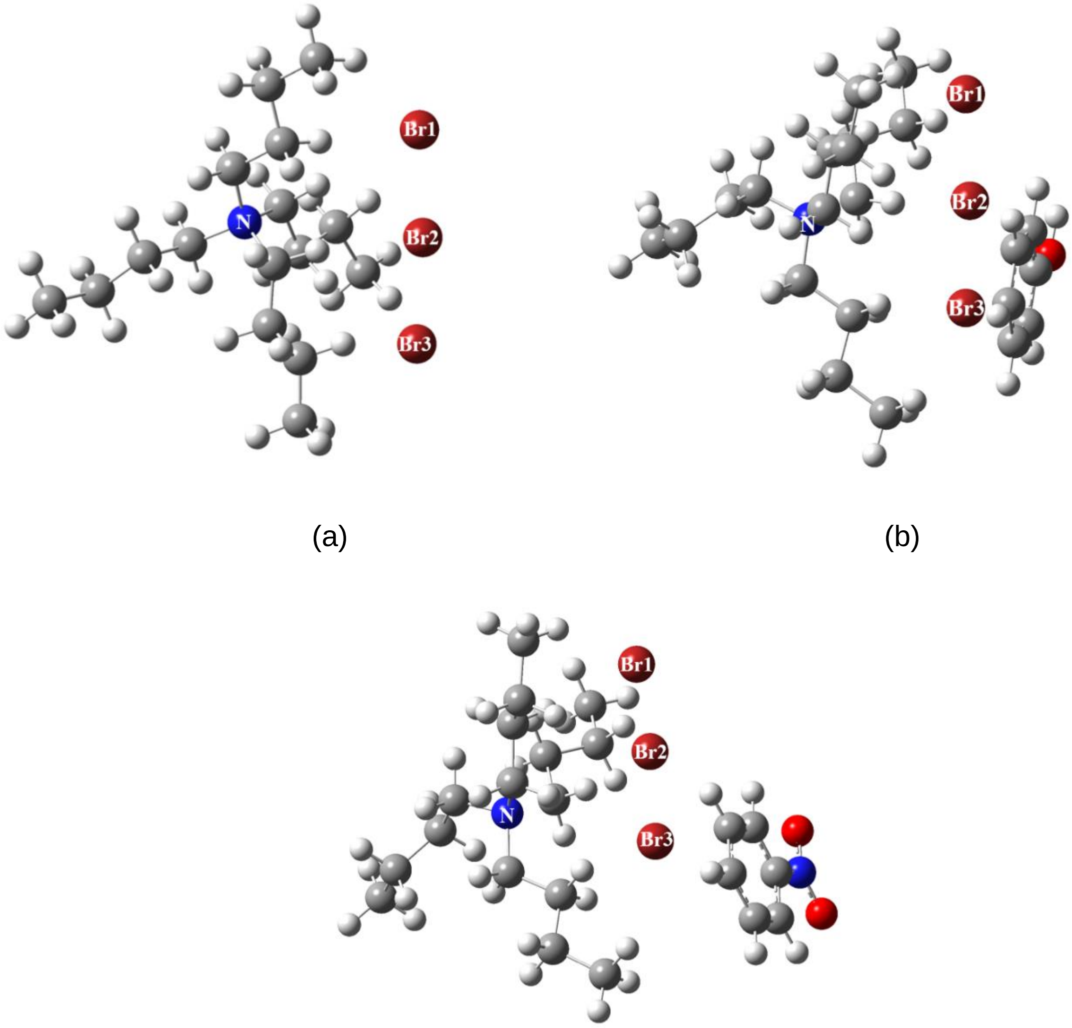
The first step to understand the mechanism of action of Br_3^- in bromination reactions to understand the how Br_3^- is formed from Br_2 and Br^-. Therefore, the structures of Br_2 and Br_3^- was optimized and analysed to evaluate the necessary parameters in understanding the formation of the Br_3^- ion. The method B3LYP hybrid functional was used along with 6-311G++(d,p) basis set. This basis set is of triple-ζ quality used for valence electrons with diffuse functions and therefore, is appropriate for geometry calculations of ions and chemical species containing lone pair(s) of electrons. The chemical and optimized structures of Br_2 and Br_3^- are shown below in table 5.1.

Table 5.1. *Chemical and optimized structures of* Br_3^-*, QATBs, TEATB, TPATB, TBATB, and CTMATB*

Abbreviations	Chemical structure	Optimized structure
Br_2	$Br—Br$	
Br_3^-	$\left[Br—Br—Br\right]^-$	

Optimization of TBATB in the presence of the substrates for understanding their influence on it.

As has been mentioned earlier, two substrates, *viz*., phenol and nitrobenzene were selected based on the ability of their respective functionalities to activate (-OH) or deactivate ($-NO_2$) the aromatic ring, and thereafter study the effect of an activated and a deactivated ring, on TBATB, which has been chosen as representative for QATBs. The structures of TBATB in presence of phenol and nitrobenzene (RM1 and RM2 respectively, RM signifies reaction mixtures) were optimized at B3LYP/6-31G(d) level of theory. Usually, the site for bromination on phenol and nitrobenzene are first the para and meta positions respectively[20–23]. Thereafter a computational study of the effect of an activated and a deactivated ring on the structure of TBATB was assessed by understanding the electronic changes in TBATB in the presence of phenol and nitrobenzene. The bond lengths Br1-Br2, Br2-Br3, and bond angle Br1-Br2-Br3 were studied along with observing the atomic charges over all the bromine atoms. The atomic charges from different population schemes were then analysed in order to justify the precision in the results. Mulliken charges, along with Natural Bond Order (NBO), Hirshfeld atomic charge, and Merz-Singh-Kollman (MK)[28] method were applied in order to determine the charges on different atoms with better precision. The structures for determining the mechanistic pathway are shown in figure 5.1 (a), (b), and (c).



(a) (b)

(c)

Figure 5.1. Optimized structures of (a) TBATB and (b) TBATB in presence of phenol (RM1) (c) TBATB in presence of nitrobenzene (RM2)

Optimization of structures for TS calculations to determine the site of attack in the Br_3^- species

The very structure of tribromide indicates that there are two sites for nucleophilic attack on this moiety, either on the central bromine atom (Br2) or on the terminal bromine atom (Br3). Figure 5.2 represents the possibilities of (a) Attack of phenol on the central bromine atom (Br2) and (b) Attack of phenol on the terminal bromine atom (Br3).

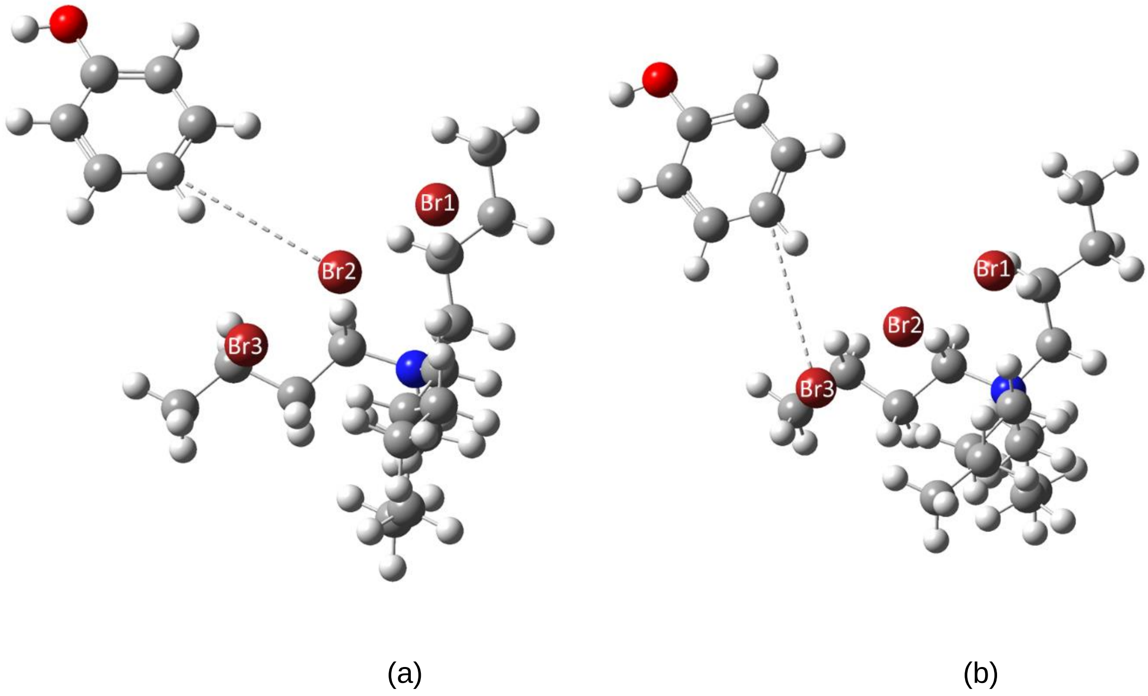


Figure 5.2. Optimized structures of (a) Attack of phenol on the central bromine atom (Br2) and (b) Attack of phenol on the terminal bromine atom (Br3)

In order to understand how nucleophilic attack by an organic substrate actually takes place on tribromide during bromination reactions, two reaction pathways were conceptualized. For the pathway involving attack on the central atom of Br_3^-, the structures were constructed in such a way that the para carbon of phenol is directed towards the central bromine atom as shown in figure 5.2 (a). On the other hand, in order to analyse the pathway involving attack on the terminal bromine atom of, the para carbon of phenol is directed towards terminal bromine atom as shown in figure 5.2 (b). Accordingly, TS calculations were performed for all the structures including the intermediates (IMs), involved in the two pathways using the QST2[29,30] method where the TSs were confirmed by the presence of one imaginary frequency each. Intrinsic Reaction Coordinates (IRC) calculations were performed in order to confirm the connection between the two local minima joining the transition states.

5.3. Results and discussion

5.3.1. Evaluating the structures of Br_2 and Br_3^-

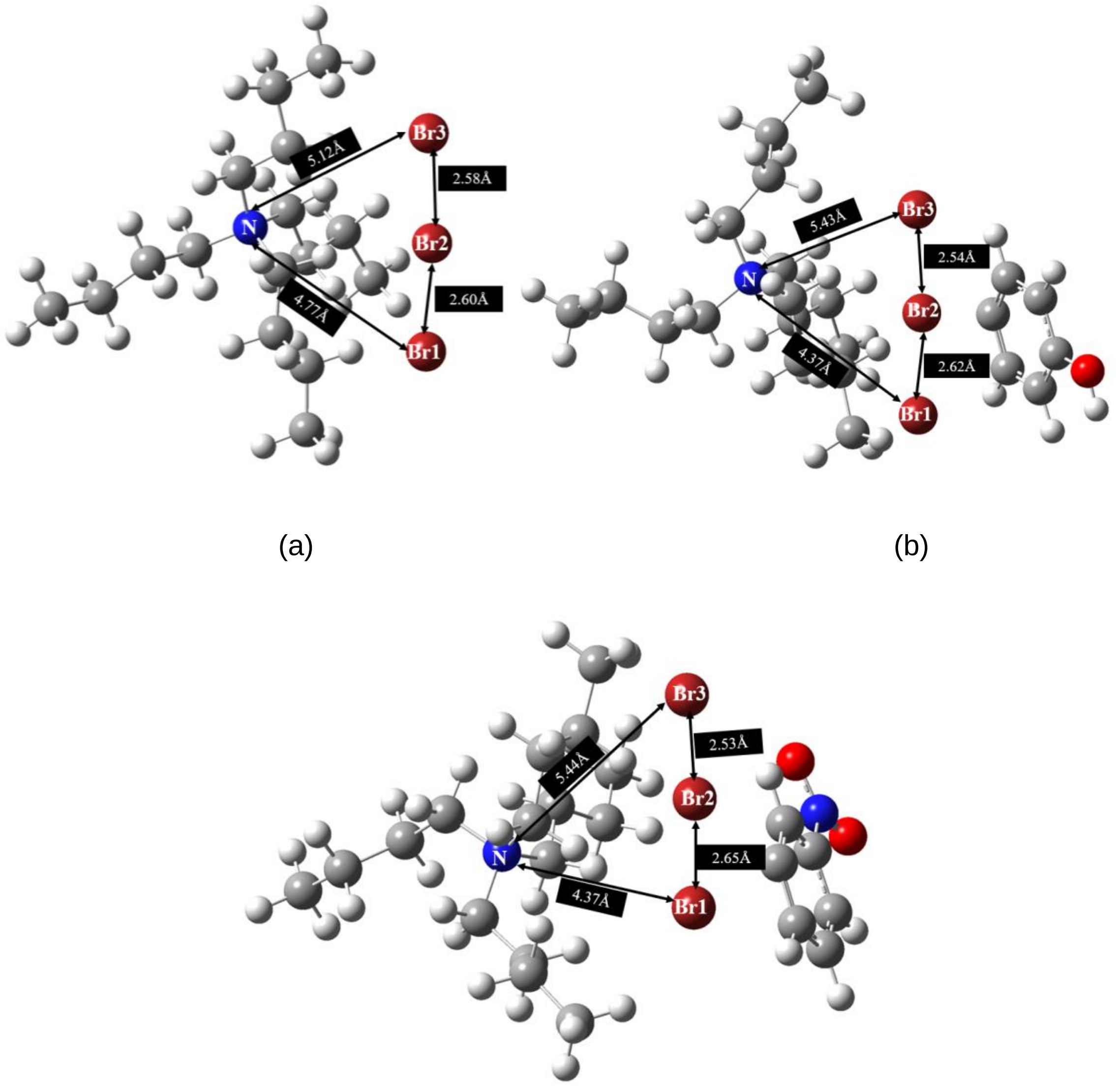
It is well reported that the Br_3^- species is formed by bonding of Br^- and Br_2[31,32]. Therefore, a computational structural analysis of Br_3^- and Br_2 was performed to determine the effects of bonding of Br^- and Br_2 to give Br_3^-, so as to understand the mode of dissociation of Br_3^-. DFT calculations showed that the Br-Br bond length was found to be 2.33 Å for the optimized structure of Br_2, however in case of Br_3^-, this bond length increased to 2.63 Å and the two terminal Br atoms are equidistant from the central Br atom in Br_3^-. The increase in bond length obviously implies bond weakening in Br_2. This observation led to the assumption that while formation of Br_3^-, Br-Br bond length in Br_2 weakens thereby bonding with Br^- to give a symmetrical moiety, a reversible process can well occur during bromination reaction by Br_3^-.

5.3.2. Understanding the changes in TBATB in the presence of phenol and nitrobenzene

The mechanism of bromination by QATBs is a long due question even though several attempts have been made to understand the same. The previous sections of the paper already provide an indication that the bromination by Br_3^- might proceed via dissociation of Br_3^- into Br^- and Br_2. In this section of the work, an attempt to comprehend and develop the mechanism by taking phenol and nitrobenzene as reference and studying the para and meta bromination of the substrates respectively. The candidates phenol and nitrobenzene were selected in order to understand the influence of their electron donating and withdrawing properties on the dissociation pattern of the tribromide ion in the presence of these substrates. The first step is to observe the changes in the structural geometry and atomic charges in TBATB in presence of these substrates. Table 5.2 presents the atomic charges and concerned bond lengths of the optimized structures of TBATB and RMs. In order to achieve a precision in the results, different population schemes have been analysed to determine the charges in different atoms; which are Mulliken charges, NBO, Hirshfeld atomic charge, and Merz-Singh-Kollman (MK) method. The optimized structures of TBATB and RMs have been shown in figure 5.3 (a), (b), and (c) respectively which displays the studied bond lengths along with symbol of the atoms. From the results obtained, it is observed that in case of TBATB, the bond distance N-Br1 is shorter than N-Br3 indicating that Br1 is closest to the nitrogen atom; in the case of RMs, N-Br1 has shorten further and N-Br3 has grown longer. The bond distance Br1-Br2 is longer compared to Br2-Br3 indicating the fact that the Br1 is more attracted towards the nitrogen atom. Thereafter while observing the optimized structure of the RMs, the bond distance Br1-Br2 have found to have lengthen further than in case of isolated TBATB; also, Br2-Br3 have grown shorter, indicating that in the presence of the selected substrates, Br1 moves closer to N, while Br2 and Br3 moves away from Br1 and N atoms. There is no major difference in the atomic charges of TBATB and RMs, however, the observable changes give some indication that there might be charge transfer from Br3 to Br2 and from Br2 to Br1 which might be because of the Br1-Br2 bond breakage, thereby releasing Br_2. From the above observations of bond length and atomic charges, it is expected that when coming in contact with phenol and nitrobenzene, TBATB might dissociate into TBAB and Br_2.

Table 5.2. *Bond lengths and atomic charges*

<table>
<tr><th colspan="2">Bond lengths (Å)</th><th colspan="2">TBATB</th><th colspan="2">RM1</th><th>RM2</th></tr>
<tr><td colspan="2">Br1-Br2</td><td colspan="2">2.60</td><td colspan="2">2.62</td><td>2.65</td></tr>
<tr><td colspan="2">Br2-Br3</td><td colspan="2">2.58</td><td colspan="2">2.54</td><td>2.53</td></tr>
<tr><td colspan="2">N-Br1</td><td colspan="2">4.77</td><td colspan="2">4.37</td><td>4.37</td></tr>
<tr><td colspan="2">N-Br3</td><td colspan="2">5.12</td><td colspan="2">5.43</td><td>5.44</td></tr>
<tr><td colspan="7">Atomic Charges (au)</td></tr>
<tr><td colspan="2"></td><td>Mulliken</td><td colspan="2">NBO</td><td>Hirshfeld</td><td>MK</td></tr>
<tr><td rowspan="4">TBATB</td><td>N</td><td>-0.41</td><td colspan="2">-0.28</td><td>0.05</td><td>0.62</td></tr>
<tr><td>Br1</td><td>-0.39</td><td colspan="2">-0.42</td><td>-0.31</td><td>-0.32</td></tr>
<tr><td>Br2</td><td>-0.05</td><td colspan="2">-0.07</td><td>-0.13</td><td>-0.10</td></tr>
<tr><td>Br3</td><td>-0.38</td><td colspan="2">-0.41</td><td>-0.33</td><td>-0.30</td></tr>
<tr><td rowspan="4">RM1</td><td>N</td><td>-0.40</td><td colspan="2">-0.28</td><td>0.08</td><td>0.10</td></tr>
<tr><td>Br1</td><td>-0.41</td><td colspan="2">-0.47</td><td>-0.33</td><td>-0.36</td></tr>
<tr><td>Br2</td><td>-0.04</td><td colspan="2">-0.06</td><td>-0.08</td><td>-0.06</td></tr>
<tr><td>Br3</td><td>-0.32</td><td colspan="2">-0.35</td><td>-0.27</td><td>-0.25</td></tr>
<tr><td rowspan="4">RM2</td><td>N</td><td>-0.40</td><td colspan="2">-0.29</td><td>0.10</td><td>0.06</td></tr>
<tr><td>Br1</td><td>-0.41</td><td colspan="2">-0.47</td><td>-0.27</td><td>-0.34</td></tr>
<tr><td>Br2</td><td>-0.04</td><td colspan="2">-0.07</td><td>-0.09</td><td>-0.10</td></tr>
<tr><td>Br3</td><td>-0.32</td><td colspan="2">-0.34</td><td>-0.15</td><td>-0.23</td></tr>
</table>



(a) (b)

(c)

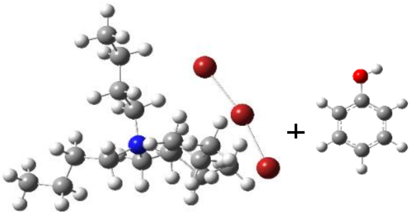
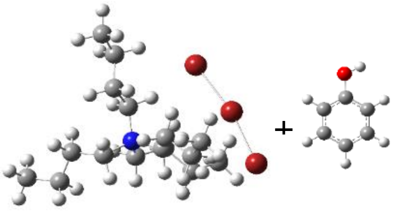
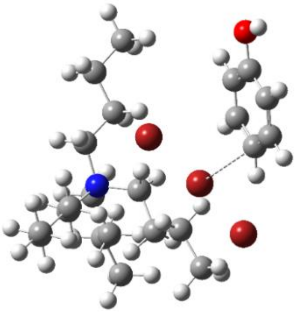
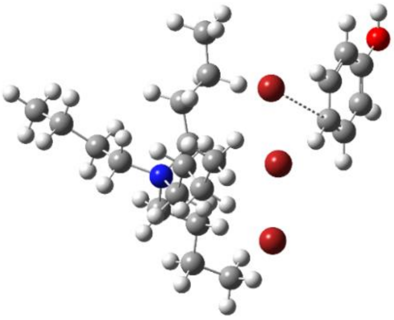
Figure 5.3. Optimized structures of (a) TBATB and (b) RM1 displaying the bond lengths N-Br1, Br1-Br2, Br2-Br3, and N-Br3 (c) RM2 displaying the bond lengths N-Br1, Br1-Br2, Br2-Br3, and N-Br3

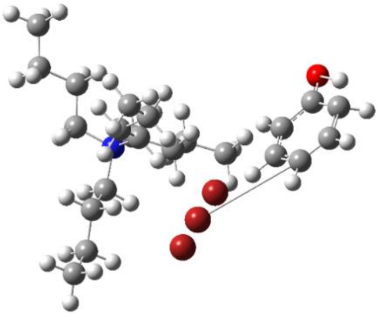
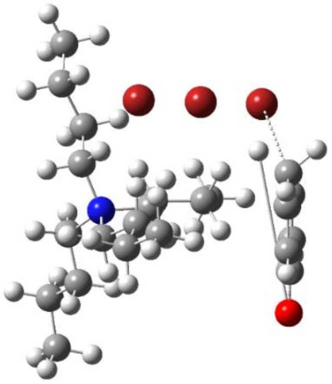
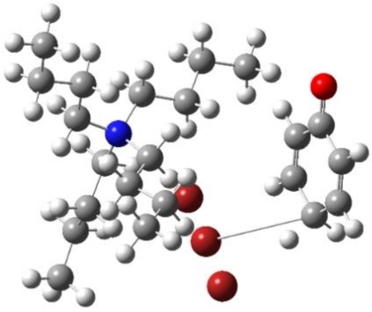
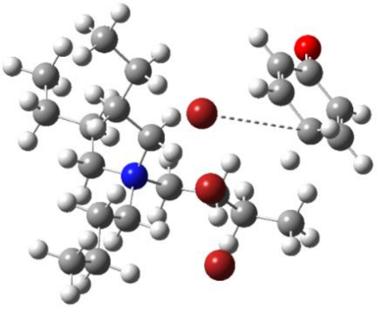
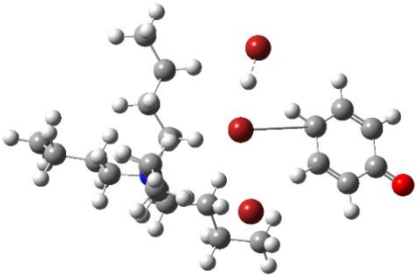
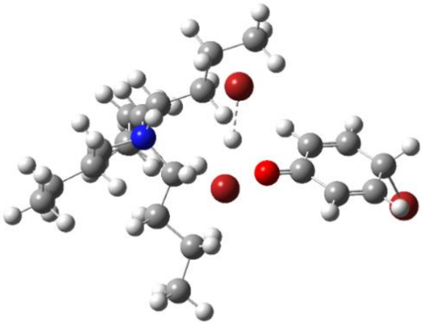
5.3.3. Determining the reactive atom in the tribromide moiety by studying the attack of phenol on the central bromine atom of the Br_3^- and attack on the terminal bromine atom of the Br_3^-

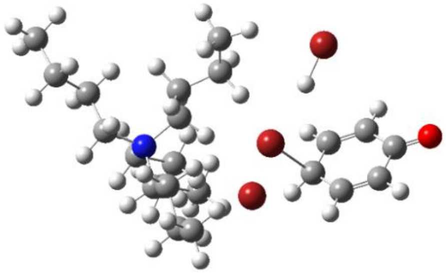
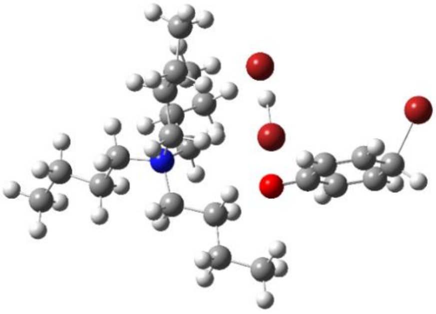
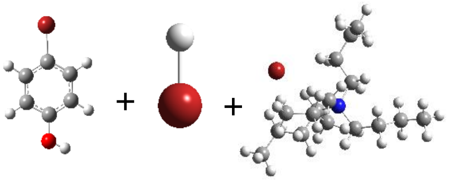
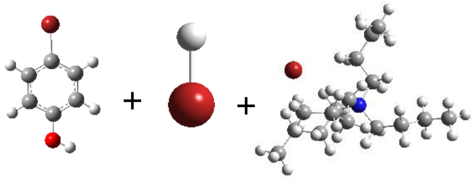
The tribromide moiety has two sites of reaction, i.e., the central bromine atom or the terminal atom. In order to have a complete understanding of the behaviour of tribromide during brominations, it was important to understand which atom took part in the reaction.

Both phenol and nitrobenzene showed similar trends in case of dissociation of the tribromide ion, therefore only phenol was chosen for the study. For this section of the work, two reaction pathways were studied along with TS calculation. All the structures involved in the two pathways are presented in table 5.3 along with their respective energies in kJ/mol.

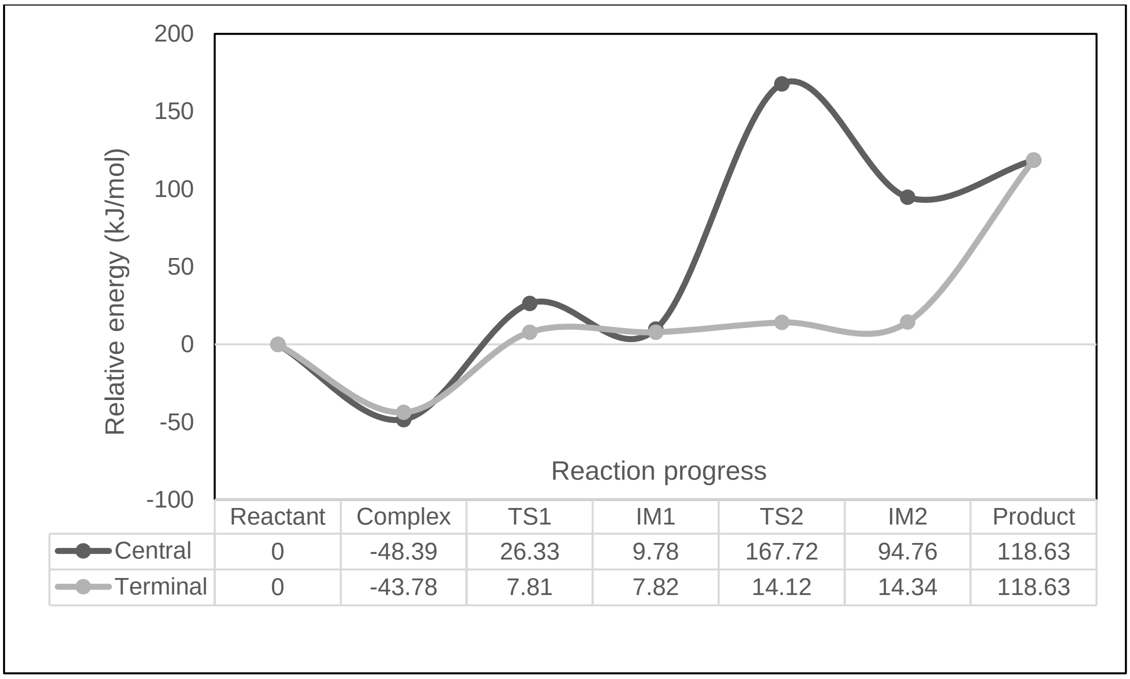
Table 5.3. *Structures involved in the two pathways along with their respective energies in kJ/mol*

Name	**Attack on the central bromine atom**	**Attack on the terminal bromine atom**
Reactant	 + 0	 + 0
Complex	 -48.39	 -43.78

TS1	 26.33	 7.81
IM1	 9.78	 7.82
TS2	 167.72	 14.12

IM2	 94.76	 14.34
Product	 118.63	 118.63

The respective graphs of the two pathways have been constructed and shown in figure 5.4. From the graphs, it can be observed that the reactants will enter the reaction pathway having energy higher than the complex, which implies towards exothermic addition of the two reactants. Thereafter, it can be observed that TS1 has a higher energy than the complex and involves lengthening of the O-H bond in phenol. It is probably TS1 where Br_2 is separated from the QATB to give Quaternary Ammonium Bromide. IM1 with comparatively lower energy than TS1 involves the detachment of the H atom from the O of the phenol leading to formation of phenoxide ion. The reaction proceeds with TS2 bearing higher energy than IM1, where the hydrogen that has been detached in IM1 is picked up by a bromine atom and forms HBr. In the same step, the para carbon of the phenol attacks either the central or the terminal bromine atom, leading to the formation of C-Br bond in the para position of the phenol. This step is followed by IM2 with a lower energy than TS2 and involves the O of the phenoxide ion to pick up an H atom from the para position. The products then obtained are TBAB, HBr and p-bromophenol. The presence of one imaginary frequency confirmed the existence of the TSs in all the cases and was further justified by IRC calculations which verified the connection of the transition states with the local minima of the reactant and the products. As can be clearly observed from the graphs, the TSs have relatively higher energy than the corresponding reactants and products, justifying the characteristic of local maxima. However, the products have an energy 118.63 kcal/mol higher than the reactants which might be because overall, it is an endothermic reaction. Analysing the graphs individually reveals that the pathway involving attack of phenol on the terminal bromine atom of the tribromide ion has species which have relatively lower energies than the pathway 1. TS1 in pathway 1 has an energy of 18.52 kJ/mol more than TS1 in pathway 2. Further TS2 in pathway 1 has an energy of 153.6 kJ/mol more than TS2 in pathway 2. Thereafter, the position of the IMs shows that IM1 and IM2 in pathway 1 have energy 1.96 kJ/mol and 80.42 kJ/mol more than IM1 and IM2 in pathway 2 respectively. Since, both the TSs i.e., TS1 and TS2 as well as IM1 and IM2 are found to have lower energies when the attack is on the terminal bromine than on the central bromine atom, the results indicate that this pathway involving attack on the terminal bromine atom is more favourable than attack on the central bromine. The respective IRC graphs have been shown in figure 5.5 below and the predicted mechanism of action is as shown below in scheme 5.3.



	Reactant	Complex	TS1	IM1	TS2	IM2	Product
Central	0	-48.39	26.33	9.78	167.72	94.76	118.63
Terminal	0	-43.78	7.81	7.82	14.12	14.34	118.63

Figure 5.4. Energy profile graphs of the two reaction pathways for phenol

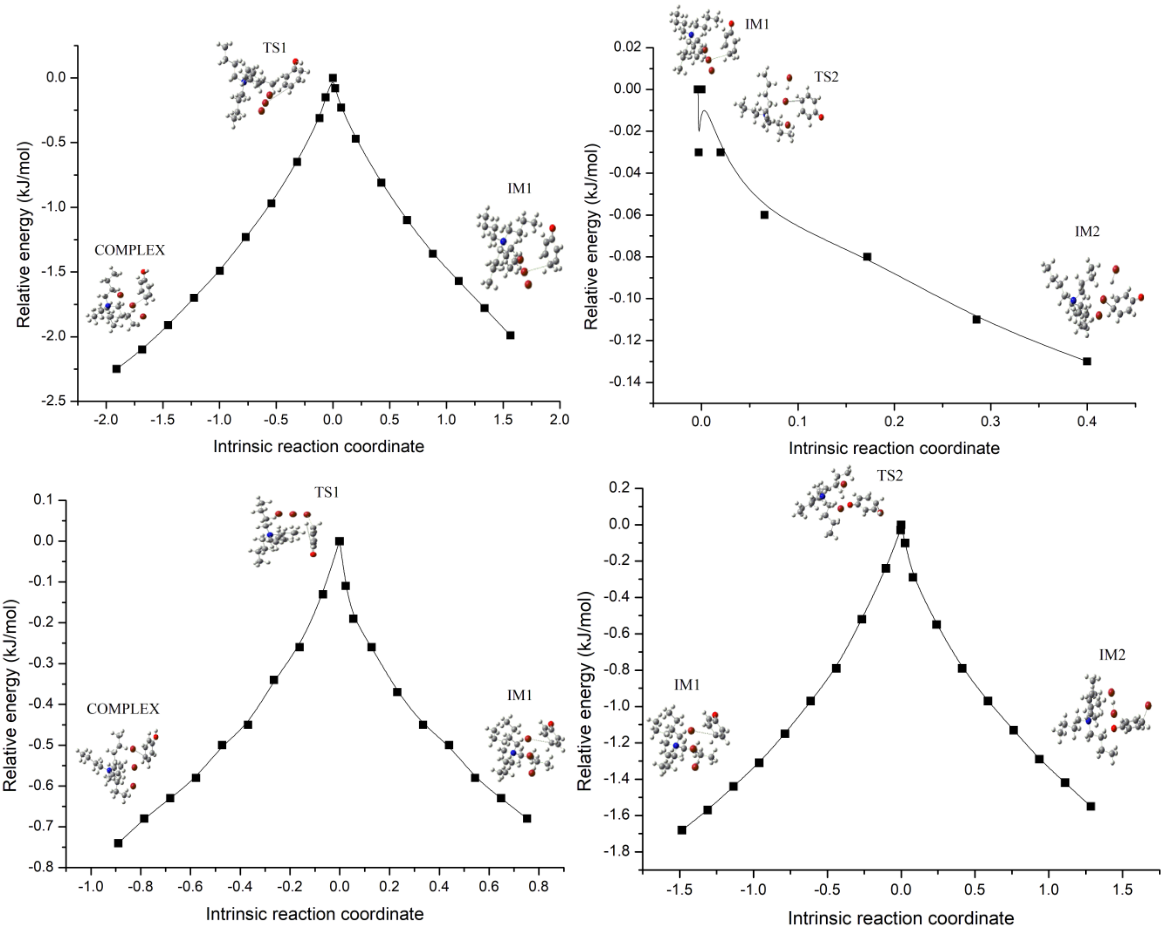
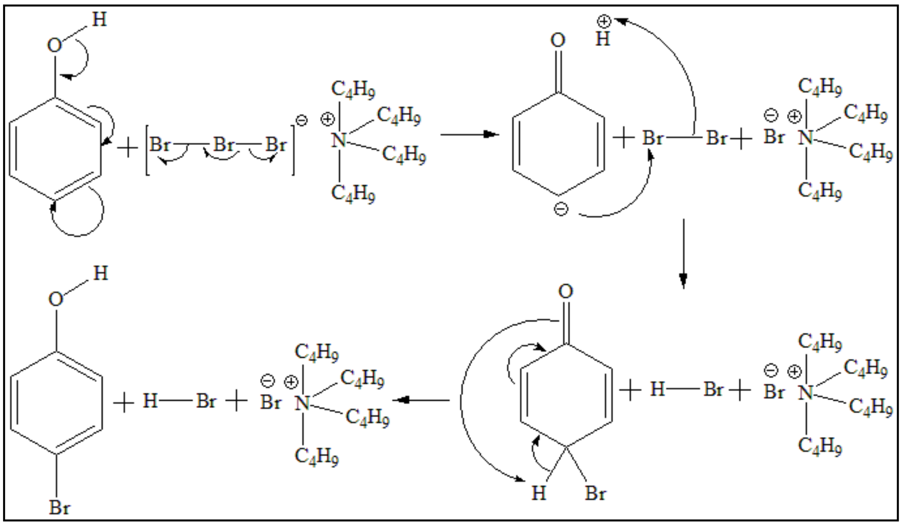


Figure 5.5. IRC graphs for TS1 and TS2 for the attack of phenol on the central bromine atom



Scheme 5.3. Proposed schematic diagram of the bromination mechanism of phenol by TBATB

5.4. Conclusion

This study was conducted with the aim to understand the mechanistic pathway of bromination reaction by TBATB, for which initially the structures of Br_2 and Br_3^- were optimized and observed to understand the formation of the Br_3^-. Thereafter the mechanistic pathway was studied by comparing the structures of TBATB without and in presence of two substrates, and lastly TS calculations were performed to determine the best possible pathway for the studied bromination reaction.

1. By observing the optimized structures of Br_2 and Br_3^-, it has been found that the Br_3^- is found from Br_2 and Br^- by bond lengthening of Br-Br in Br_2. Thus, it can be assumed that this process might be reversible in while bromination reaction by Br_3^-, i.e., breakage of one Br-Br bond.
2. Furthermore, a comparison of the optimized structure of TBATB with and without the presence of phenol and nitrobenzene was made so as to explain the changes in the geometry and atomic charges of the reagent. The results revealed that when TBATB was optimized in the presence of phenol and nitrobenzene, there were certain variations in its structure: the bromine atom (Br1) moved and came closer in

case of the RMs, the bond length Br1-Br2 have lengthen further in case of the RMs. The observable changes in the atomic charges of TBATB and the RMs indicate that there might be charge transfer from Br1 to N and from Br2 to Br3 which might be because of the Br1-Br2 bond breakage, thereby releasing Br_2. From the above observations of bond length and atomic charges, it is expected that when coming in contact with the substrates, TBATB might dissociate into TBAB and Br_2.

3. Subsequently, two reaction pathways were studied, one involving attack of phenol on the central bromine atom of the tribromide ion of TBATB, and the other involved attack on the terminal bromine atom. By making a comprehensive observation of the various transition states and intermediates involved in both the pathways, it can be concluded that the bromination of phenol by TBATB most probably takes via attack of phenol on the terminal bromine atom of the tribromide of TBATB. This attempt of understanding the reaction mechanism of bromination reaction by QATBs have been a long due question and it is expected that the findings of this work might aid researchers to tune reactions according to one's requirements.

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Chapter 6

Correlating the Efficiency and Greenness of Solvents through a Study of their Influence on TBATB

The role of solvents in any reaction goes beyond just providing a reaction medium as solvents have an immense effect on the rate of the reaction. However, some solvents pose serious threats to humans and the environment. Therefore, it becomes important to find a balance between the benignity of solvents and their efficacy. Thus, this chapter explains the details of a pareto-optimal presentation of the efficiency of solvents and their respective greenness.

The work described in this chapter has been published in:

Sustainable Chemistry and Pharmacy, **2021,** Volume 20, 100387.

6.1. Introduction

6.1.1. Solvents and their associated hazards

With the advancement of green chemistry, the hazards associated with the chemicals and chemical processes came into limelight. Amongst the various categories of chemicals, organic solvents have mostly been criticized due to their underlying hazards. Solvents like pentane[1], heptane[2], hexane[3], carbon tetrachloride (CCl_4)[4,5] pose serious threats to the human health as well the environment. Continuous exposure to these solvents can lead to skin irritation, dizziness, damage of the kidneys, liver, or central nervous system etc[1–5]. Despite the fact that all the above-mentioned risks involved with solvents indicates towards their avoidance in synthetic processes[6], they still remain as an integral part of most chemical reactions. The reason for this is that they significantly influence the stability and solubility of compounds and is responsible for molecular associations of reactants throughout the reaction[7,8]. The most important factor is that solvents are usually used in bulk amounts, thereby further intensifying their hazardous effects. Hence, it becomes imminent that risks associated with these solvents are extremely serious and should not be ignored.

6.1.2. Methods for solvent selection

Given that solvents continue to remain an essential component of most chemical reactions, it is vital to identify green and sustainable solvents and thereby develop comprehensive techniques, tools, and frameworks for solvent selection. As the level of hazard of solvents differ from each other, data sheets or solvent selection guides[9–12] are useful since they allow solvents' ranking based on ease of waste disposal, health, and safety concerns, and so on. The GlaxoSmithKline's (GSK's) solvent selection guide is one such excellent resource which has been acknowledged to be a reliable tool for solvent selection, and it has been recommended by a number of researchers for selecting their preferred solvent[13–15].

6.1.3. Bromination by QATBs and influence of solvents

Different organic transformations have recently been explored through the field of green chemistry, and among the many reactions studied, bromination reactions have received a lot of attention[16–18]. The most commonly used reagent for this transformation has been molecular bromine (Br_2)[19], despite its highly dangerous nature and intrinsic toxicity. Because of the unfavorable aspects of bromine, new environmentally preferable chemicals have been developed. Among the most successful replacements to molecular bromine are the Quaternary Ammonium Tribromides (QATBs), also known as Br_2 carriers. Among the several QATBs, tetrabutylammonium tribromide (TBATB) has risen to prominence due to its efficiency and versatility[20–22]. Bromination reactions are normally carried out in a solvent medium, and literature studies suggest that a variety of solvents have been utilized for various reactions including both polar[21,23] as well as non-polar solvents[24] are appropriate for these reactions.

6.1.4. Reactivity parameters and DFT

The efficacy of any reagent is determined by a number of factors, including ease of dissociation, stability in any solvent, chemical potential, chemical hardness, electrophilicity, and so on[25–27]. For TBATB, these factors, like those of all other reagents, could be influenced by the solvent system in which the reaction is carried out. And thus, it is necessary to evaluate the effects of various solvents on the reagent, allowing for the selection of the most suitable green solvents. One of the most practical approaches to examine reaction profiles is to undertake computational calculations prior to wet lab investigations, considering it entirely eliminates the danger of risk of hazards and the potential waste of chemicals. Density functional theory (DFT)is one such popular technique for modelling experiments since it produces results that are nearly precise with the experimental findings[28] at an affordable computing cost. Therefore, an attempt is made through this study to examine the effects of various solvents on the behavior of both TBATB and bromine. A set of fourteen solvents like pentane[24], hexane[29], heptane[24], cyclohexane[30], CCl_4[31], ethyl acetate[32], acetic acid[33], trifluoro acetic acid[34], tert-butyl alcohol(t-BuOH)[35], ethanol[36], methanol[37], acetonitrile[21], dimethyl sulfoxide (DMSO)[38], and water[39] have been chosenbased on a review of bromination reactions in literature. The electronic parameters calculated and analyzed in this study are dissociation energy, highest occupied molecular orbital (HOMO) - lowest unoccupied molecular orbital (LUMO) energy gap, chemical hardness, chemical potential, and electrophilicity. A comprehensive review of literature suggested that these parameters indicate about the reactivity of compounds[25–27,40]. Following that, the GSK's solvent selection guide[41] was referred to determine the greenness of each of these solvents in order to build a greenness-efficiency correlation. Through the introduction of alternative green solvents, this study is expected to serve as a springboard for more research into chemically efficient and environmentally benign solvent options.

6.2. Materials and methods

TBATB is a well-known quaternary ammonium tribromide which is a combination of a tetrabutyl ammonium cation and a tribromide ion (Br_3^-), in which the negative charge is dispersed over the three bromine atoms. In organic reactions TBATB is frequently considered as a carrier of bromine and it is supposed that mechanistically during any reaction, this reagent loosely dissociates into TBA^+ (cationic part) and Br_3^- (anionic part) (Scheme 6.1) and thereafter Br_3^- further dissociates into Br_2 and Br^- (Scheme 6.2).

$$\mathrm{TBATB} \longrightarrow \mathrm{TBA}^{+} + \mathrm{Br}_3^{-}$$

Scheme 6.1. Dissociation of TBATB into TBA^+ and Br_3^-

$$\mathrm{Br}_3^{-} \longrightarrow \mathrm{Br}_2 + \mathrm{Br}$$

Scheme 6.2. Dissociation of Br_3^- into Br_2 and Br^-

In order to comprehend the influence of the solvent medium in the behavior of this reagent, appropriate computational studies were done with a series of solvents. All the computational calculations were carried out in the Gaussian 16[42] suite of program applying density functional theory with the B3LYP hybrid functional and 6-31g (d,p) basis set. The structures were built with precision and visualized using the GaussView6[43] Graphical User Interface. Along with optimization of the structures, vibrational frequency analyses were also performed in order to elucidate the zero-point vibration energies (ZPE).The characteristics of local minima was corroborated by the absence of any imaginary frequency in the matrices of energy second derivatives (Hessian).

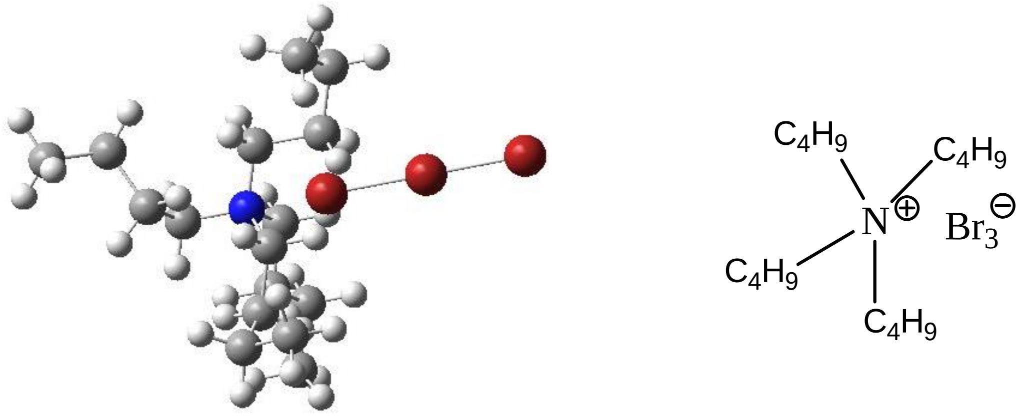
Among the other descriptors investigated in this work, DFT was employed to determine the dissociation energy of TBATB into TBA^+ and Br_3^-, as well as Br_3^- into Br_2 and Br^-. Furthermore, the energy gaps of HOMO and LUMO of TBATB and Br_3^- were calculated in the studied solvents. Lastly, for understanding the influence of the solvents on the reactivity parameters of the reagent, molecular descriptors like chemical hardness, chemical potential, and electrophilicity were also calculated and analyzed.

Elucidation of optimized structure of the TBATB, TBA^+, Br_3^-, Br_2 and Br^-

B3LYP/6-31g(d,p) level of theory was employed for optimizing the structures of TBATB, TBA^+, Br_3^-, Br_2 and Br^-, which were further subjected to vibrational frequency analyses. The calculations were carried out in the Gaussian16 software by individually incorporating the implicit solvent models of (i) pentane, (ii) hexane, (iii) heptane, (iv) cyclohexane, (v) CCl_4, (vi) ethyl acetate, (vii) acetic acid, (viii) trifluoroacetic acid, (ix) t-BuOH, (x) ethanol, (xi) methanol, (xii) acetonitrile, (xiii) DMSO, and (xiv) water. The optimization process necessitated the creation of fourteen input files for each of the moieties, one for each solvent. The polarizable continuum model (PCM)[44] was used to add all fourteen solvents separately for each input file, which involved placing the solute in a void surrounding by the solvent, which was considered as a continuum characterized by its dielectric constants. The PCM has its own set of constraints, such as the absence of solute-solvent charge transfer[45] and the imposition of a boundary between the solute and the solvent, which thereby may result in a reduction in dielectric behavior at the molecular level[46]. The PCM, however, is one of the most accurate continuum models due to its two key features: the use of a surface charge distribution to define the polarization of the surroundings and the inclusion of a molecular cavity containing the actual geometry of the analyzed system. The existence of these two characteristics allows PCM to be employed for solutes of any shapes and charge distribution, thereby making it a highly versatile method. It is an easy to use and computationally economical tool which can be applied for determining the important impacts of solvents on the characteristics and reactivity of diverse molecular systems[47].

The optimized structure of TBATB is presented below in figure 6.1:

Color key: Br N C H
● ● ● ●



(a) (b)

Figure 6.1. (a) Optimized structure of Tetrabutyl ammonium tribromide along with (b) chemical structural formula

Studies on the role of solvent in the dissociation of tribromide

Tetrabutylammonium tribromide dissociation can be thought of as a sequential process in which the quaternary ammonium cation $[N(CH_3)_4]^+$ and the tribromide anion Br_3^- first move apart from one another, then Br_3^- dissociate into Br_2 and Br^-. We wanted to see if the surrounding solvent had an effect on the energy associated with these events. As a result, in all 14 solvents, two associated metrics, namely the change in N-Br distance and the dissociation energy of TBATB, were investigated.

6.2.1. N-Br bond length

Study to determine the influence of solvent on N-Br bond length during dissolution

The dissociation of TBATB into $[N(CH_3)_4]^+$ and Br_3^- is caused by lengthening of the N-Br distance. As a result, it's reasonable to suppose that the longer the N-Br bond, the weaker the bond strength and the easier it is to dissociate. The goal of the first experiment was to see if the length of the N-Br bond changed as the solvent medium changed. As a result, the N-Br bond length in each solvent medium was determined in order to evaluate the ease with which the Br_3^-anion might be released into the solution, which could provide information on the reagent's efficacy in each solvent.

6.2.2. Dissociation energy

Following with the assumption that the solvent affects the release of Br_2 from TBATB, the most efficient solvent for bromination reactions will be the one that causes the TBATB reagent to dissociate most readily, first into TBA^+ and Br_3^- (Scheme 6.1), and then into Br_2 and Br^- (Scheme 6.2). DFT was used to compute the dissociation energies of TBATB and Br_3^- in various solvents, and the equations were constructed as follows:

$\Delta E_1 = E_{TBATB} - (E_{TBA^+} + E_{Br_3^-})$

Where, ΔE_1 = Dissociation energy of TBATB;

E_{TBATB} = Energy of optimized TBATB;

E_{TBA^+} =Energy of optimized TBA^+;

$E_{Br_3^-}$ =Energy of optimized Br_3^-

The dissociation energies of Br_3^- in various solvents were computed similarly as shown below:

$\Delta E_2 = E_{Br_3^-} - (E_{Br_2^+} + E_{Br^-})$

Where, ΔE_2 = Dissociation energy of Br_3^-;

$E_{Br_3^-}$ = Energy of optimized Br_3^-;

E_{Br_2}=Energy of optimized Br_2;

E_{Br^-} = Energy of optimized Br^-

6.2.3. HOMO-LUMO profiles and energy difference

The energy gap of HOMO-LUMO signifies a compound's stability and thus its reactivity as demonstrated by the negative magnitude of their energies[48].A molecule with a short E_{HOMO}–E_{LUMO} energy gap indicates greater polarizability, thus displaying intramolecular charge transfer from the electron donor to the electron acceptor[49]. It has been documented that the HOMO and LUMO energies of any compound are affected by the solvent, thus affecting the HOMO-LUMO energy gap[40,50]. As a result, the HOMO – LUMO profiles of TBATB and Br_2 were created in order to examine their energy distribution and energetic behavior, and thereby to better understand their chemical reactivity. The calculations were carried out in each of the fourteen solvents to determine how the solvent affected their reactivity. The function "CubeGen" existing within the GaussView6 graphical user interface was used to generate all the MO diagrams.

Studies on the role of solvent on bromine (Br_2)

6.2.4. Chemical Hardness (η)

Chemical hardness can be described as the capacity of a chemical species to withstand changes in its electrical configuration. It is a crucial descriptor because it indicates the species' chemical stability, and hence its reactivity[51]; reports imply that the harder the molecule, the lower its reactivity, and vice versa[51]. Given that Br_2acts as the active brominating agent in the last stage, hardness, which is a descriptor of reactivity, has been investigated for Br_2 in all solvents.

Chemical hardness was calculated using the formula given below[52]:

$$\eta = \frac{E_{LUMO} - E_{HOMO}}{2}$$

6.2.5. Chemical Potential (μ)

The chemical potential of any compound can be defined as the rate of change of free energy, as a result of change in the number of electrons. It is a measurement of an electron's inclination to leave a molecule, and the lower the value of μ, the easier it will be to gain an electron or more difficult it will be to lose an electron. The formula below was used to calculate the change in chemical potential of Br_2 in various solvent systems[52]:

$$\mu = \frac{HOMO + LUMO}{2}$$

6.2.6. Electrophilicity (ω)

The electrophilicity of any compound determines its ability to accept an electron pair[53] and higher the electrophilicity, more will be its reactivity as an electrophile[54]; and vice versa. The electrophilicity of Br_2 in all the studied solvents was investigated in order to identify its electrophilic ability in various solvents. Electrophilicity was calculated using the formula given below[53,54]:

$$\omega = \frac{\mu^2}{2\eta}$$

where, μ and η signifies chemical potential and chemical hardness respectively.

6.3. Results and discussion

The negative effects of solvents have become a major global concern and is a well-known fact, which is why a number of solvents have now been banned or restricted. However, it must be acknowledged that solvents play a crucial part in chemical reactions, and there is enough everyday laboratory experience to confirm that under the influence of certain solvents, reactions tend to complete more quickly and generate superior product yields. As a result, while solvent greenness will always be the primary issue, it must be accepted that proper solvent selection is also a critical necessity. For example, bromination reactions using TBATB, have been investigated since many years now, and it can be seen that the solvents used in these experiments have been gradually changed over time[19–22,37,55].The change in solvent in this reaction was probably motivated by the environmental concerns about the toxicity of many of the organic solvents formerly utilized. However, acknowledging the fact that solvents should ideally be both efficient and ecologically friendly, it becomes necessary to investigate the role of these solvents in bromination processes and compare their efficiency to their greenness. A group of fourteen different solvents have been chosen for this specific work considering literature reports on their involvement in bromination reactions using TBATB as well as other brominating agents. Taking into account the fact that TBATB dissociates into TBA^+ and Br_3^- in any reaction medium, followed by Br_3^- dissociation into Br_2 and Br^-, computational methods have been extensively employed to observe the ease with which TBATB dissociates into TBA^+ and Br_3^-, and then to Br_2 as depicted in schemes 6.1 and 6.2.The behavior of Br_2 in the presence of the engaged solvents have been examined more thoroughly as Br_2 is expected to be liberated from TBATB and is the active species responsible for bromination of the substrates.

6.3.1. Efficiency of TBATB in different solvent media

Since easier dissociation of reagent correlates with higher reagent activity, an assessment of the ease of separating TBATB into $N(CH3)_4^+$ and $Br_3^-$and hence Br_3^- into Br_2 and $Br^-$was carried out. The distance between N and Br in TBATB was first calculated, and table 6.1

shows the various N-Br distances between $N(CH_3)_4^+$ and Br_3^-. The results show that the bond length of N-Br is longest in ethanol (4.7278), implying that the easiest separation is achieved when ethanol is used as the solvent, followed by hexane (4.6330). An intriguing note is that, whereas CCl_4 was formerly the solvent of choice for TBATB, from table 6.1, it can be seen that this solvent did not actually facilitate facile separation of Br_3^- from TBATB.

Thereafter the dissociation energy was calculated and from the results it can be observed that the energy requirement for dissociation of TBATB is lowest in pentane solvent medium (ΔE_1 = -313.7342 kJ/mol) followed by heptane (ΔE_1 = -307.6372 kJ/mol) as presented in table 6.1. Br_3^- showed a trend similar to TBATB and was found to dissociate easier in pentane solvent medium (ΔE_2 = -145.574 kJ/mol) followed by hexane (ΔE_2 = -144.5158 kJ/mol) and heptane (ΔE_2 = -143.7202 kJ/mol). A higher magnitude of ΔE (it is to be noted that in all the concerned cases the sign of ΔE is negative) indicates which solvent facilitates easier dissociation of the reagent and therefore, based on the lower dissociation energies of TBATB and Br_3^- in pentane, heptane and hexane as compared to other solvents, it can be assumed that these solvents are expected to have higher efficiency in the bromination reactions by TBATB. Interestingly dissociation energy of Br_3^- into Br_2 and Br^-, was also found to be lowest in pentane (seen in table 6.1). From these results of step-wise dissociation of TBATB, it can be inferred that solvents such as ethanol, hexane, heptane, and pentane might assist better in the dissociation of TBATB into $N(CH_3)_4^+$ and Br_3^- and thereby Br_3^- into Br_2 and Br^-.

The energy gap of HOMO and LUMO was evaluated in all fourteen solvents in order to examine the compound’s reactivity in the presence of various solvent systems. The results (as shown in table 6.1) demonstrate a trend that is somewhat similar to the dissociation energy results i.e., the HOMO-LUMO energy gap was observed to be smallest under the presence of pentane (energy gap for TBATB = 3.9026 eV) and is followed by heptane closely (energy gap for TBATB = 3.9040eV). As previously stated, a smaller energy gap of HOMO and LUMO signifies easier intermolecular charge transfer, thereby resulting in higher reactivity. This suggests that the reactivity of TBATB in pentane and heptane maybe higher than in the other solvents under investigation.

Table 6.1.*Molecular descriptors of TBATB calculated at B3LYP/6-311G level of theory*

Dielectric Constant	**N-Br (Å)**	**ΔE_1 (in kJ/mol)**	**ΔE_2 (in kJ/mol)**	**HOMO-LUMO energy gap of TBATB (eV)**
Pentane 1.84	Ethanol 4.7278	Pentane -313.7342	Pentane -145.574	Pentane 3.9026
Hexane 1.88	Hexane 4.6330	Heptane -307.6372	Hexane -144.5158	Heptane 3.9040
Heptane 1.92	t-BuOH 4.49632	Acetic Acid -211.1928	Heptane -143.7202	CCl_4 3.9111
Cyclohexane 2.02	Water 4.4817	Trifluoroacetic a. -191.3574	Cyclohexane -141.2294	Methanol 3.9312
CCl_4 2.24	DMSO 4.4777	Hexane -177.3434	CCl_4 -136.9316	Acetic Acid 3.9334
Ethyl Acetate 6.02	Acetonitrile 4.4748	Cyclohexane -164.5098	Ethyl Acetate -111.0928	Trifluoroacetic a. 3.9356
Acetic Acid	Methanol	CCl_4	Acetic Acid	Hexane

6.2	4.4743	-152.9814	-110.6534	3.9410
Trifluoroacetic a. 8.55	Acetic Acid 4.4519	Ethyl Acetate -74.2716	Trifluoroacetic a. -106.5948	t-BuOH 3.9432
t-BuOH 12.5	Trifluoroacetic a. 4.4492	t-BuOH -59.3502	t-BuOH -103.2148	Cyclohexane 3.9478
Ethanol 22.4	Ethyl Acetate 4.4471	Ethanol -49.4364	Ethanol -99.5722	Ethanol 3.9671
Methanol 32.6	Heptane 4.3556	Methanol -39.5226	Methanol -98.6934	Water 3.9671
Acetonitrile 37.5	Pentane 4.3539	Acetonitrile -38.8934	Acetonitrile -98.4542	Ethyl Acetate 3.9674
DMSO 46.7	Cyclohexane 4.3465	DMSO -37.3178	DMSO -97.8406	Acetonitrile 3.9674
Water 79.7	CCl_4 4.3358	Water -35.295	Water -97.0554	DMSO 3.9674

The dissociation of TBATB aids the release of bromine, which is considered as the actual brominating agent. As a result, after examining the findings for TBATB and Br_3^-, the influence of solvents on Br_2 were studied. Initially, the energy gap of the HOMO and LUMO of Br_2 was calculated for understanding its stability and reactivity in the presence of the studied solvents. Table 6.2 presents the results of HOMO-LUMO energy gap of Br_2 and as can be observed the energy gap is smallest in the pentane solvent medium (energy gap for Br_2 = 3.8975 eV) implying that under its influence, Br_2 might be most reactive, since as already stated earlier, a smaller HOMO-LUMO energy gap corresponds to better intermolecular charge transfer. As shown in table 6.2, hexane (energy gap for Br_2 = 3.8980 eV) and heptane (energy gap for Br_2 = 3.8986 eV) also show potential.

Following that, the chemical hardness (η) of Br_2 was computed (Table 6.2) in order to determine the chemical resistance of Br_2in the investigated solvent media. A lower value of η signifies a softer molecule, thereby implying enhanced reactivity and vice versa. As the results in table 6.2 clearly demonstrates, in the presence of pentane solvent medium, the lowest value of η was achieved (η = 1.9487 eV), followed by hexane (η = 1.9490 eV) and heptane (η = 1.9493 eV). As a result, it can be deduced that when Br_2 is exposed to pentane, hexane, or heptane, it will act as a softer molecule, exhibiting better reactivity as comparison with when exposed to other solvents.

In addition, the chemical potential (μ) of Br_2 was investigated in order to evaluate its electron accepting power, and the results revealed a divergence from the expected trend when compared to the other parameters. The results of μ of Br_2 as presented in table 6.2 shows that μ is lowest in CCl_4 solvent medium (μ = -5.7470 eV), and then in pentane (μ = -5.7447 eV), hexane (μ = -5.7445 eV) and heptane (μ = -5.7442 eV). As fact suggests, a more negative value of μ signifies easier electron gain, from the results, it can be said that under the influence of CCl_4, pentane, hexane, and heptane, Br_2 might operate as a stronger electron acceptor than in other solvents.

Finally, the electrophilicity (ω) of Br_2 in the specified solvents was investigated in order to assess its ability as an electrophile; that is, its ability to receive a pair of electrons. The results of ω showed a trend similar to that of the HOMO-LUMO energy gap and chemical hardness. Table 6.2 presents the results of ω of Br_2 and as can be seen the value is highest in case of pentane (ω= 8.4675 eV) which is followed by hexane (ω = 8.4655eV) and heptane (ω =

8.4635 eV). Therefore, as a higher value of ω corresponds to higher reactivity as an electrophile, it can be assumed that when Br_2 is exposed to these solvents, it will operate as a stronger electrophile, thereby exhibiting superior reactivity.

According to these findings, in bromination reactions using TBATB and Br_2, non-polar solvents may have an advantage over polar solvents.

Table 6.2. *Molecular descriptors of Br_2 calculated at B3LYP/6-311G level of theory*

Dielectric Constant	**HOMO-LUMO energy gap of Br_2(eV)**	**η (eV)**	**μ (eV)**	**ω (eV)**
Pentane 1.84	**Pentane** 3.8975	**Pentane** 1.9487	**CCl_4** -5.7470	**Pentane** 8.4675
Hexane 1.88	**Hexane** 3.8980	**Hexane** 1.9490	**Pentane** -5.7447	**Hexane** 8.4655
Heptane 1.92	**Heptane** 3.8986	**Heptane** 1.9493	**Hexane** -5.7445	**Heptane** 8.4635
Cyclohexane 2.02	**Cyclohexane** 3.9002	**Cyclohexane** 1.9501	**Heptane** -5.7442	**Cyclohexane** 8.4576
CCl_4 2.24	**CCl_4** 3.9135	**CCl_4** 1.9568	**Cyclohexane** -5.7434	**CCl_4** 8.4395
Ethyl Acetate 6.02	**Ethyl Acetate** 3.9263	**Ethyl Acetate** 1.9632	**Ethyl Acetate** -5.7357	**Ethyl Acetate** 8.3790
Acetic Acid 6.2	**Acetic Acid** 3.9266	**Acetic Acid** 1.9633	**Acetic Acid** -5.7356	**Acetic Acid** 8.3780

Trifluoroacetic a. 8.55	**Trifluoroacetic a.** 3.9312	**Trifluoroacetic a.** 1.9656	**Trifluoroacetic a.** -5.7349	**Trifluoroacetic a.** 8.3662
t-BuOH 12.5	**t-BuOH** 3.9350	**t-BuOH** 1.9675	**t-BuOH** -5.7343	**t-BuOH** 8.3565
Ethanol 22.4	**Ethanol** 3.9391	**Ethanol** 1.9696	**Ethanol** -5.7337	**Ethanol** 8.3459
Methanol 32.6	**Methanol** 3.9405	**Methanol** 1.9702	**Methanol** -5.7336	**Methanol** 8.3426
Acetonitrile 37.5	**Acetonitrile** 3.9405	**Acetonitrile** 1.9702	**Acetonitrile** -5.7336	**Acetonitrile** 8.3426
DMSO 46.7	**DMSO** 3.9416	**DMSO** 1.9708	**DMSO** -5.7336	**DMSO** 8.3403
Water 79.7	**Water** 3.9424	**Water** 1.9712	**Water** -5.7334	**Water** 8.3382

6.3.2. Correlating between solvent efficacy and greenness

The overarching concern about solvent greenness must be addressed concurrently with any debate about solvent efficacy. As a result, in order to make a rational assessment of the studied solvents' efficiency, a study of their greenness was conducted using the GSK guide for solvent selection as a reference[41], and their impact on health and the environment, as well as their flammability, were used as reference factors for the current study. The GSK solvents guide assigns a score to each factor, ranging from 1 to 10, with 10 being the most environmentally friendly. According to calculation methodology developed by Prat *et al.*[11] and the GSK's guide, some solvents have an EHS (environment/health/safety) red flag, which indicates that the solvent has a known or probable regulatory issue[41]. As a result, a score of 8 has been deducted from these flagged solvents in order to achieve a genuine outcome. The scores of the three factors were totaled together, with an additional 8 points deducted for EHS-flagged solvents. Depending on the overall greenness of the solvents, the sum of the scores is colored green, yellow, or red, with green signifying greener solvents and red indicating dangerous solvents. Table 6.3 highlights the greenness ranking of the solvents under study according to their health impact, environmental impact and flammability.

Table 6.3. *The greenness ranking of the studied solvents based on GSK guide for solvent selection*

Solvents	Health	Environmental impact	Flammability	EHS flag	Sum
Pentane	8	6	2	-8	8
Hexane	4	3	2	-8	1
Heptane	8	3	3		14
Cyclohexane	7	5	2		14
CCl_4	3	5	4	-8	4
Ethyl Acetate	8	8	4		20
Acetic Acid	6	8	8		22
Trifluoroacetic acid	6	5	7		18
t-BuOH	9	6	6		21
Ethanol	8	8	6		22

Methanol	5	9	5		19
Acetonitrile	6	6	6		18
DMSO	7	5	9		21
Water	10	10	10		30

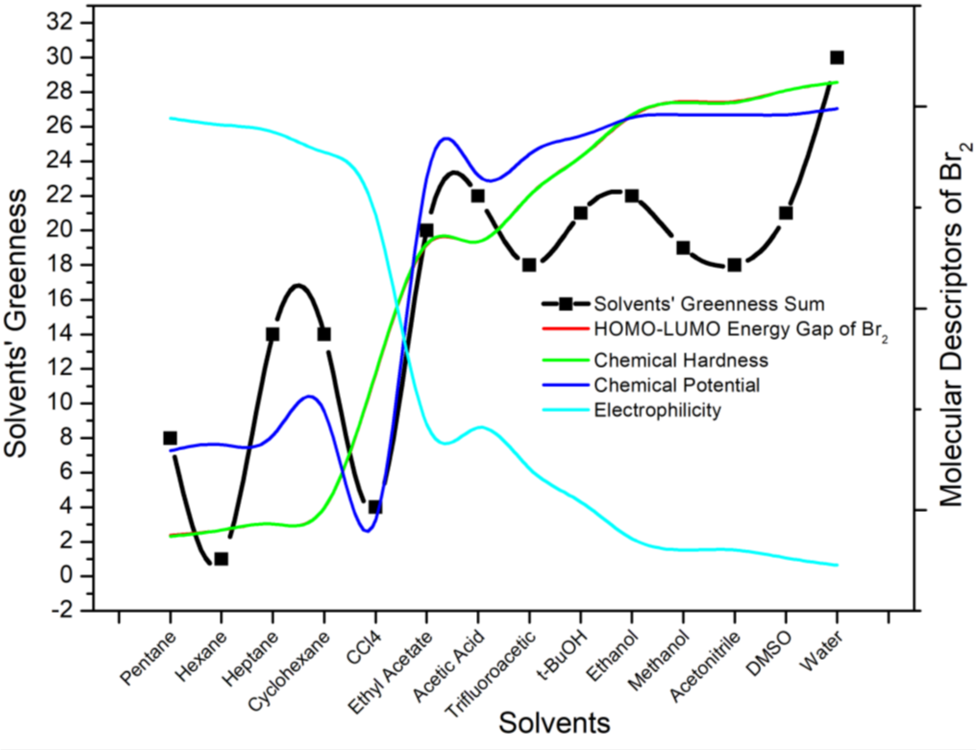


Figure 6.2. Correlation graph of studied solvents' greenness and their respective efficiencies

A comparative graph has been shown in figure 6.2 in order to provide a better understanding of the studied correlation. The graph above depicts a distinct relationship between the greenness of the investigated solvents and their respective efficiencies. According to GSK's solvent selection guide, the broad black curve reflects the total of the solvents' greenness, while the red, green, blue, and cyan colors represent the HOMO-LUMO energy gap, chemical hardness, chemical potential, and electrophilicity of Br_2, respectively. Because it is predicted that Br_2released from TBATB during the reaction is the active brominating agent, the chemical descriptors of Br_2 were chosen to better explain the correlation. As can be observed from the graph, solvents with a greater solvents' greenness sum have larger HOMO-LUMO energy gaps, chemical hardness, and chemical potential and smaller electrophilicity values, and vice versa. As previously stated, a bigger value of HOMO-LUMO energy gap and chemical hardness suggests lower reactivity, whereas a lower chemical potential implies easier electron gaining ability, and a higher value of electrophilicity signifies better electron accepting ability. As a result of the aforementioned graph, it can be deduced that solvents near the left end of the curve will most likely perform better in the examined reaction than those towards the right end.

The above correlation graph displays a clear view of the greenness and efficiency of the investigated solvents, with pentane being identified as a high-risk solvent, despite its efficiency being higher than the others. As a result, a chemist is always faced with a dilemma when choosing the correct solvent, since the efficiency of the solvent medium and its greenness may not always complement one other. And which is why, a middle path must be found where the greenness is reasonably high while the positive chemical influence on the reagent's reactivity is likewise significant. A deeper examination of the graph reveals that, according to computational calculations, heptane may be the best solvent for TBATB related bromination reactions, as its greenness sum is moderately greater than the other solvents at the left end, as represented by the broad black curve. The findings of this study are important because they open up the possibility of more investigation into non-traditional green solvents as options for various other chemical transformations.

6.4. Conclusion

Through this work an attempt has been made to understand the influence of different solvents on the reagent TBATB. After assessment of various parameters, a co-relation between efficiency and greenness of the solvents was developed which led to the realization that greenness and efficiency may not necessarily complement each other in any particular reaction. Based on the computational assessment of reactions involving TBATB, a correlation graph was developed and it led to the conclusion that heptane could be an ideal choice of solvent for these reactions as it strikes a balance between reactivity and toxicity.

6.5. References

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Appendix 2

List of Conferences/Seminars/Webinars/Workshops Attended

- **Poster presentation** at National Seminar on ‘**Chemistry in Interdisciplinary Research (NSCIR-2017)’**, organized by Department of Chemistry, Nagaland University, Lumami, held on 16th and 17th March, 2017.
- **Oral presentation** at DBT Sponsored **National Seminar on Bio-resource Exploration and Utilization: Application in Modern Biology** organized by Bioinformatics Infrastructure Facility (BIF) Centre, Nagaland University, Lumami, held on 9th and 10th October, 2018.
- **Oral presentation** at National Seminar on ‘**Chemistry in Interdisciplinary Research (NSCIR-2018)’**, organized by Department of Chemistry, Nagaland University, Lumami, held on 9th and 10thNovember, 2018.
- **Attended** the Sensitization Workshop on **DST-Women Scientist Schemes (WOS)** organized by DST, New Delhi and Nagaland University, held on 4th and 5th March, 2019.
- **Attended** the One-day Workshop on “**Importance of IPR in Academic Institutions**” organized by IPR Cell, Nagaland University, held on 29th May, 2019.
- **Attended** theWorkshop on ‘**Research Ethics, Paper Writing & IPR**’ organized &sponsored by UGC-SAP (DRS-III), Department of Botany and Advanced Level Institutional Hub, Nagaland University, Lumami, held on 14th and 15th November, 2019.
- Webinar Series on “**Advances in Materials Science and Technology (WSAMST-2020)**” organized by department of Applied Sciences and Humanities (Physics), School of Engineering, University of Petroleum and Energy studies, Dehradun, held during 22nd – 26th June, 2020.
- **Attended** the “**Online training workshop on Computational Density Functional Theory**” organized by Thanthai Periyar Government Polytechnic College, Vellore, held on 4th and 5th July, 2020.

- **Attended** the **India International Science Festival 2020 (IISF 2020)** organized by Ministry of Science and Technology; Ministry of Earth Sciences, and Ministry of Health and Family Welfare, Govt. of India in collaboration with Vijnana Bharati (VIBHA) by Council of Scientific and Industrial Research (CSIR), held during 22nd – 25th December, 2020.
- **Oral presentation** at **2nd Annual Convention of North East (India) Academy of Advances in Sciences and Technology (NEAST) and International Seminar on Recent Advances in Science and Technology (IRSRAST)** organized by NEAST, Mizoram University, Aizawl, held during 16th – 18th November, 2020.
- **Oral presentation** at National e-Seminar on "**Chemistry in emerging trends of interdisciplinary research**" organized by Department of Chemistry, Nagaland University, Lumami, held during 18th – 20th November, 2020.
- **Attended** the Virtual Short Term Training Programme on "**Chemistry from computational tools for beginners (CCTB-2022)**", organized by Department of Chemistry, SVNIT, Surat, Gujarat, held during 1st -5th March, 2022.

Appendix 3

List of Publications

- **R. Karmaker**, N. B. Kuotsu, A. Ganguly, N. Guchhait, U. B. Sinha. A theoretical and experimental study on the effect of cationic moiety of quaternary ammonium tribromides in bromination reactions. *Chemical Physics Letters*. Elsevier. **2018.**
- **R. Karmaker**, D. Sinha, U. B. Sinha. Rationalizing between the efficiency and greenness of solvents- A computational study of their influence on TBATB. *Sustainable Chemistry and Pharmacy.* Elsevier. **2021**.
- **R. Karmaker**, N. Longkumer, K. Richa, D. Sinha, U. B. Sinha. A computational approach to understanding the mechanism of aromatic bromination using quaternary ammonium tribromides. *Journal of the Indian Chemical Society*. Elsevier. **2022**.
- K. Richa, **R. Karmaker**, N. Longkumer, V. Das, P. J. Bhuyan, M. Pal and U. B. Sinha. Synthesis, *in-vitro* evaluation, Molecular Docking and DFT studies of some Phenyl Isothiocyanates as anticancer agents. *Anti-Cancer Agents in Medicinal Chemistry*. Bentham Science. **2018.**

- P. C. Bhomick, A. Supong, **R. Karmaker**, M. Baruah, C. Pongener, D. Sinha. Activated carbon synthesized from biomass material using single-step KOH activation for adsorption of fluoride: Experimental and theoretical investigation. *Korean Journalof Chemical Engineering*. **2019**.

- N. Longkumer, K. Richa, **R. Karmaker**, V. Kuotsu, A. Supong, L. Jamir, P. Bharali, U. B. Sinha. Green Synthesis of Bromo Organic Molecules and Investigations on Their Antibacterial Properties: An Experimental and Computational Approach. *Acta ChimicaSlovenica*. Slovenian Chemical Society. **2019.**

- M. Baruah, A. Supong, P. C. Bhomick, **R. Karmaker**, C. Pongener, D. Sinha. Batch sorption–photodegradation of Alizarin Red S using synthesized TiO_2/activated carbon nanocomposite: an experimental study and computer modelling. *Nanotechnology for Environmental Engineering.* Springer. **2020**.

- K. Richa, **R. Karmaker**, T. Ao, N. Longkumer, B. Singha, U. B. Sinha. Rationale for antioxidant interaction studies of 4-bromo-1-isothiocyanato-2-methylbenzene – An experimental and computational investigation. *Chemical Physics Letters*. Elsevier. **2020**.
- A. Supong, P. C. Bhomick, **R. Karmaker**, S. L. Ezung, L Jamir, U. B. Sinha, Dipak Sinha. Experimental and theoretical insight into the adsorption of phenol and 2,4-dinitrophenol onto Tithonia diversifolia activated carbon. *Applied Surface Science.* Elsevier. **2020**.
- S. Kumar, S. Sharma, **R. Karmaker**, D. Sinha. DFT study on the structural, optical and electronic properties of platinum group doped graphene. *Materials Today Communication*. Elsevier. **2020**.
- N. Longkumer, K. Richa, **R. Karmaker**, B. Singha, U.B. Sinha. Facile Green Synthesis of Bromoaniline Molecules: An Experimental and Computational Insight into their Antifungal Behaviour. *Asian Journal of Chemistry.* Asian Publishing Corporation. **2022.**
- N. Longkumer, K. Richa, **R. Karmaker**, B. Singha, U.B. Sinha. Experimental and Theoretical Investigations on the Antibacterial Activity of some Bromoaniline Compounds. *Anti-infecrtive Agents*. Bentham Science. (Accepted, 2022)
- N. Longkumer, K. Richa, **R. Karmaker**, B. Singha, U.B. Sinha. Exploring the Antioxidant Activity of Bromoanilines: An Experimental and Computational Approach. (Under Review)

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Appendix 1

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Name of the department and school	Department of Chemistry, School of Sciences
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