

# PANJAB UNIVERSITY RESEARCH JOURNAL (SCIENCE)

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**PANJAB UNIVERSITY RESEARCH JOURNAL (SCIENCE)**  
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**Professor Renu Vig**  
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**PANJAB UNIVERSITY,**  
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**MESSAGE**

The Panjab University Research Journal (PURJS) is a prestigious journal published by Panjab University regularly since 1950. It's a pleasant moment that journal has completed 75 years of publication and is coming out with platinum jubilee issue volume 75, year 2025.

The journal has been publishing scientific articles received from faculty, scholars, from India and abroad. Its copies are distributed to various libraries and subscribers in India and abroad and it has a wide readership base. It covers latest discoveries and developments in all fields of science and is a platform for dissemination of innovative findings.

An eminent panel of editors have steered journal publication since its inception and have been able to make it informative and useful for readers. Panjab University has always supported journal publication in all forms and has a vision to develop it further in coming years. The very fact that journal is relevant and growing in its readership base even after 75 years of existence makes it a proud endeavour of Panjab University.

I invite faculty/scholars/scientists to share their scientific works through PURJS and wish the stakeholders all the best.

  
(Renu Vig)



## **Editor in chief**

### **PANJAB UNIVERSITY RESEARCH JOURNAL (SCIENCE)**

Panjab University Research Journal, Science (PURJS) is a premier scientific journal published annually by Panjab University, Chandigarh. It's a matter of great pride that the journal has completed 75 years of its regular publication and is coming out with the volume 75, 2025.

PURJS started as "Research Bulletin of East Panjab University" in the year 1950 and continued with this name till 1953. It had 41 Bulletin covering different scientific domain in the period (volume 1-3). In the year 1954 it was named "Research Bulletin of Panjab University" and continued with this name till the year 2002. From the year 1954 till 1958 (volumes 4-9) it published Bulletin 42 to 156. From the year 1959 (volume 10) it started publication in new format. Professor Vishwanath D.Sc. (Cantab), F.N.I. (Editor-in-Chief) played a pivotal role in the development of the journal since its inception.

PURJS is in wide circulation at National & International level and has reciprocal arrangement with various International Institutions who send their journals in lieu of receiving PURJS copies. There is a large base of subscribers who have subscribed to the journal and they are provided with printed hard copies of the volumes.

In this platinum issue we have a range of articles starting with a write up on Prof. Vishwanath by Prof. RC Sobti, ex-vice Chancellor of Panjab University; article on Physics Department, PU by Prof. Satya Prakash and on Mathematics Department, PU by Prof. Surinder Pal Singh Kainth and Prof. Arun Grover, ex-vice Chancellor of Panjab University. Prof. Renu Vig, vice Chancellor, Panjab University has contributed an informative article on Artificial intelligence alongwith Dr. Garima Joshi. Other articles provide useful insights into various aspects of scientific disciplines.

We look forward to continued successful journey of this prestigious journal by publishing useful and informative articles in the coming years.

**Prof. Desh Deepak Singh**

Editor-in-Chief, PURJS



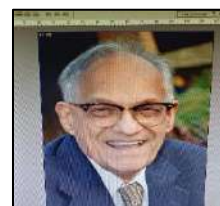
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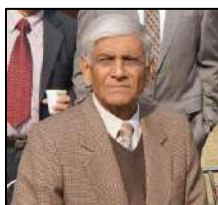
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## VISHWA NATH: REMEMBRANCE OF GREAT SCIENTIST AND DOYEN OF ZOOLOGY AND ONE OF THE FOUNDERS OF PU CAMPUS AT CHANDIGARH

R C Sobti<sup>1</sup>, Sanjeev Puri<sup>2</sup>

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Dr. Vishwa Nath one of the most prolific researcher and a hardcore teacher of Zoology was among the pioneers in setting up the department of Zoology at Panjab University, Chandigarh. The path to this success story was arduous specifically after the partition when the Main Zoology remained in Lahore where he worked as a zoologist. His exemplary journey is credited to his simplistic yet very progressive family background. Mr Vishwa Nath was the Youngest among the five Children born to Pt Baij Nath. A visionary father and pioneer in the field of education and set up a school Famously known as Pt Baij Nath School ( PBN School) and later named as PBN senior secondary school one of the biggest school at that time. Pt Baij Nath though himself studied till 8<sup>th</sup> but made single handed efforts to provide both the education and sports activity to the children at that time around his area in Amritsar. While studying in his father's school his father noticed an extraordinary potential and exceptional combination of being a keen student and a sportsperson and mentored him personally. This mentorship from his father continued till 10 more years. His father's illness for three years culminated into his demise. The loss of his father together with the rituals being practiced at that time left an indelible mark on the sensitive mind of young Vishwa Nath. While

another jolt later due to the demise of his mother left him orphan affecting every sphere of his life.

Young Vishwa Nath after completing matriculation in his father's school then joined Govt College at Lahore (now in Pakistan) as a science student. His father's mentorship and training enabled Mr Vishwa Nath to blossom as a Science scholar while equally talented sportsperson and got selected a member of the Punjab University Cricket team. His talent was recognized the late Maharaja Bhupinder Singh of Patiala, who offered him a position of Professor at Mohindra college Patiala while Vishwa Nath was in his fifth year. At a very young age he devoted himself completely to set up a research laboratory in the college while also continue to bring laurels to the college in sports as well.

Mr Vishwa Nath joined Trinity Hall at Cambridge in 1923 and completed his thesis entitled "*Cytology of Reproductive Organs of Scorpions and Mosquitos*" under the direct supervision of Dr James Gray. This work was then approved for his PhD Degree by University of Cambridge in record two years of time span. While in abroad he was also got selected in the university Cricket team there and became *Cambridge Blue*. On his return Dr Vishwa Nath was selected as Lecturer at Govt College Lahore, where he dedicated his life to research and sports. While at Lahore he

organized Punjab University Cricket Association and remained as president for many years.

The tenacity and perseverance in any task that Dr. Vishwa Nath's undertook together with his unprejudiced, open mindedness coupled with simplicity made him a person with exceptional qualities. These virtues of him were liked by both his colleagues and students equally. Even the exceptional observation during his research and relating it with life made him a different person altogether. Observing microscopically dead cork during his research activity infused in him thought of the force that keep the cells living. These thoughts spurred in him the search for his answers which he derived from Gita and became an ardent reader to seek the answers whenever one is being required to be sorted out. Within two years he read and memorized Gita and started class of Gandhi prayer in Govt. College Hoshiarpur.

He was a visionary to the core who remained focused to what ever learning he Got from his father. While professor at Govt College Lahore, he initiated teaching and practical course on Protozoa to students of B.Sc. Zoology in every summer and open to all any and every student irrespective of college university and area. This visionary approach is something which is in line with the latest education policies in the current time. Besides Teaching Dr Vishwa Nath also showed keen interest in research and published excellent defining publications one in the *quarterly journal of Microscopical Science* in 1932 entitled "*The Spermatid and the sperm of crab Paratelphus spinigera*" and later another in the *Journal of Morphology* in 1937 entitled "*Spermatogenesis of Prawn Palaemon Lamarrei*". He produced evidence to demonstrate that spermatozoon explodes at the time of fertilization and also provided the mechanism for it. The

pioneer work of Dr Vishwa Nath was recognized and he was elected as Fellow of then National Institute of Science of India ( Currently The Indian National Science Academy) in 1940. In 1942 he produced a monograph on *The Dcapod Sperm in the Transactions of the National Institute of Science in India*. Towards the end of this year he was elevated to the Chair of the Professor of Zoology in Govt College at Lahore. This position was vacated by Dr George Matthai who was also professor of zoology in the college simultaneously. Prof Vishwa Nath tremendously contributed to the development of Zoology and also presided over the section of Zoology of the Indian Science Congress held at Delhi and there he delivered his famous address on *The Golgi Apparatus*. In recognition of his contributions he was also awarded *ScD* degree of the University of Cambridge early in 1929. He also remained as Emeritus Scientist of the Council of Scientific and Industrial Research of the Govt of India. Later in 1968 Prof Vishwa Nath was awarded the Joy Gobinda Law Memorial Gold Medal by the Asiatic Society Calcutta for his outstanding work in the field of Zoolgy.

After the painful events of partition Dr Vishwa Nath also moved to India wherein he was first got an appointment for a short stint as Principal at Govt College Dharamshala ( Now in Himachal Pradesh)but later joined a Principal of Govt College Hoshiarpur in 1948. Here in the verandahs of the college he started the department of Zoology. In the mean time Dewan Anand Kumar who was working as Reader in dept of Zoology and also Dean of University Instructions at Lahore was appointed Vice -Chancellor of East Panjab University ( Now in Chandigarh). Prof Vishwa Nath who got retired from his Govt

Service in 1952 was given appointment as Professor of Zoology. His vision and focus helped in the growth of the department and more staff was hence inducted. This led to his visionary outcome of research in the field of Zoology which he continued to inculcate among his young faculty. In the furtherance of his efforts towards research Dr Vishwa Nath started the publication of *Research Bulletin ( Science) of Panjab University*. In September 1959 Dr Vishwa Nath retired again from Panjab University but continued as *Chief Editor of the Research Bulletin (Science)* in an Honorary capacity. His commendable research focus was recognized enabling him to join as Head of Zoology department at Jodhpur University, where he set up a school for research in cytology. After Two years of active contribution at Jodhpur University, Panjab university on account of his exceptional contribution to the field of Zoology conferred upon Dr Vishwa Nath the title of *Prof Emeritus* in the department of Zoology at Panjab University. Besides his Academic contribution Dr Vishwa Nath also actively participated in facilitating and executing various policies at Panjab University as Fellow of Syndicate and Senate and also as *Dean of Faculty of Science and Mathematics* at the university.

Dr Vishwa Nath continued to delve on updating himself while also providing platforms for young faculty to embark on the journey of the animal world. He produced two text books, one in 1961 on *A Text Book of Zoology* and later in 1964 on Chordates for B.Sc. Students. Both these books were dedicated to the memory of his father who saw in him the zeal to reach to this level. Asia Publishing House in 1965 specifically brought out Dr Vishwa Nath's most important monograph on *Animal Gametes (Male)*. This work was

rightly dedicated to Pt Jawaharlal Nehru, then Prime Minister and an architect of science development in the country. The most salient aspect of this monograph was that the work presented in this was carried out by himself as well as his pupils and his colleagues while working in the department of Zoology first at Lahore then Hoshiarpur and finally at Panjab University. Using light microscope, he demonstrated in this monograph the morphological and cytochemical account of the spermatogenesis in large variety of animals both from invertebrates and vertebrates. He also went on to successfully correlate the findings as being observed using electron microscope. A similar Monograph on *Animal Gametes (Female)* was then published by him in 1968 dedicating it to his Professor Sir James Gary, Kt. F.R.S in commemoration of his 75<sup>th</sup> birthday and his distinguished years of service to the development of Zoology at University of Cambridge. Dr Vishwa Nath Never stopped working and in 1970 he produced another book dedicating to his Pupils and entitled it "*Cell Biology*" detailing about the cell inclusion bodies like Golgi bodies, Mitochondria, centrioles, nucleoli etc. dedicating it to his pupils. Through out his research endeavours Dr Vishwa Nath laid great emphasis on vesicular form of Golgi body. Accordingly each vesicle is provided with osmiophilic and argentophilic cortex and osmiophobic and argentophobic medulla. He further went on the explain and also validated through histochemical staining that to start with the Golgi is granular and soon gets differentiated to duplex and binary vesicles. He also figured few Crescent shaped Golgi elements which have chromophobic sphere attached to its concave side. His interest and thorough observations that fatty yolk in egg is directly formed from Golgi by gradual growth

process was later supported by histochemical studies both by his collaborators and himself. He also established presence of RNA in Mitochondria .

All the work of Dr Vishwa Nath provided his credential as one of the foremost cytologist of the country. He left a mark and a lineage which is continued till date in the form of his pupils who are taking on the baton handed over by him in the

furtherance of human life in general and zoology specifically.

This article has been written on the basis of information available in the biography of Dr Vishwan Nath written by Late Dr G.P Sharma Former Head Department of Zoology Panjab University for Indian National Science Academy for their compilation of great scientists of India and some personal knowledge of RCS.

# PANJAB UNIVERSITY PHYSICS DEPARTMENT

## ACADEMIC AMBIANCE

**Prof. Satya Prakash**

Department of Physics, Panjab University, Chandigarh

### **Introduction**

Panjab University has beautiful complexes geometrically spread up all around for the intellectual and physical fitness of university fraternity. The Administrative Block building in gray cement color was facing the beautiful water pond with lotus flowers on the carpet of green leaves on the water surface; depicting the look of immense beauty. The water fountains in the middle of pond were generating the cool ambiance.

As one moves from administrative building block towards north east; one moves in the world of science consisting building blocks of chemistry, physics, geology, anthropology and zoology departments in one row and building blocks of chemical engineering, mathematics, statistics, instrumentation science and botany departments in the other row. These blocks are inter connected by covered corridor promoting interdisciplinary teaching and research and providing interactive ambiance to students and teachers.

Then there are sports complex and botanical gardens to relax and to do fitness exercises after intellectual work. The entrance in the central library building block amounts to be in intense intellectual ionosphere and if one is tired, one can enjoy the delicious food and indoor games in students center. One can learn the ideals of “truth is God” and “Ahinsa perm dharma” in

lotus shape Gandhi Bhavan and then one can have the glimpses of history of Indian arts and culture in Arts Museum building.

However, if one is walking in the shades of beautiful plants on both the sides of road, one feels as if one is walking in nature in the center of intellectual environment to gain energy to move forward, to learn, to ponder over unknown and to contribute with one’s utmost capacity in the domains of science, literature and arts to enrich the knowledge for well-being of all.

### **Building Block**

The grandeur of building block of physics department is shown in Fig. 1. It houses the teaching class rooms, teaching laboratories, the department library and



**Figure 1**

teachers tea room where the faculty members meet two times in a day to enjoy tea and to discuss physics and administrative issues of the department. Then there are research laboratories of nuclear physics, particle physics, solid state

physics, atomic spectroscopy and geochronology evenly housed from basement to third floor. The students enjoy the tea and snacks in their canteen near the entrance of physics department. There is spacious parking place for vehicles.

The department consists of very specific research laboratory of variable energy cyclotron. This is one of the oldest proton accelerator machines which is still operative to do nuclear physics and material science experiments.

### **Knowledge Dispersion**

There was Honors School (HS) system of integrated four years teaching to lead to BSc (HS) and MSc (HS) degrees. In the first two years the students were taught physics as major subject and two subsidiary subjects preferably chemistry and mathematics needed to understand physics. In year three students were taught only physics as major course. The course contents were higher than the course contents of MSc-I of other universities. The BSc (HS) students with grades above a certain level were taught one more year for their MSc (HS) degree. The half yearly examinations were held in the month of December and annual examinations in the month of March.

There was nothing like class or caste discrimination among the students and teaching faculty. Each one of them was there on one's own merit. The students were thoroughly trained to work hard and to be disciplined. These well-trained students were excelling in various fields of public and academic lives in the country and abroad.

However, with modern thoughts on education it was argued that the single examination in an academic year may not be justified to examine in detail the level of knowledge of the student. Therefore, semester system of teaching and

examination was introduced probably in 1978. The course contents of annual system were reorganized nearly in two equal parts. There were two end semester examinations and one house test in each semester. The final result was the weighted average score of all the four examinations. Certainly, this was the better system to evaluate the students.

When MPhil became pre requisite for lecturer post in colleges, department started MPhil program. This was also pre-PhD advanced course and of more demanding nature from the students. Most of the students in MPhil class were from MSc (HS). These were bright students. Therefore, it was not difficult to manage and to inspire them to work hard. They were well adopting the intricacy of subjects and intelligently responding in the class. Later on they were joining PhD program in the department or going for teaching job in the colleges.

However, when college teachers with limited knowledge of advances in subject were allowed to join this program to get MPhil degree in stipulated time, these courses have to be redesigned to achieve this objective. The MPhil degree lost its competitive spirit.

It was nearly the beginning of 1982; it was decided to start four semesters MSc course for the bright BSc graduates from the colleges. The admissions were merit based. The course contents of core courses were designed keeping in view the back ground of these students in BSc course. In principle MSc (HS) students were better exposed to physics due to the course contents in BSc (HS) and in MSc (HS) than these MSc students.

Then there was National Educational Policy 1986; known as 10+2+3 system. Now the HS

system was extended to 5 years; BSc (HS) degree course of three years duration and MSc (HS) degree course of two years duration. Accordingly MSc courses were also redesigned. With all these constraints two post graduate courses of MSc (HS) and MSc degrees were going on well.

However, it was year 1991 or so, the university administration decided that post graduate degree of same nomenclature be given to the students of both the post graduate classes. The department administrative and academic committees decided that MSc (HS) degree be awarded to all the students. This equality was disheartening to one set of students and an advantage to other set of students.

The academic ambiance in the physics department was very positive. The motive was to help the students; they learn to learn on their own to achieve what they want to achieve in life. The teachers were putting their best to promote the creativity among students and the students had the faith in their teachers. The students were serious in the classrooms as well as in the library to acquire the knowledge. The teacher taught relations were cohesive and of mutual respect. Fig. 2 shows the students working seriously in department library to understand the complexities of basics of physics.



**Figure 2**

### **Knowledge Creation**

The faculty members were engaged in research activities and they were working hard with their PhD students to obtain substantial research output. The research students were coming to do research and teachers were also training them to be an innovative researcher. The PhD thesis was the byproduct of these efforts. The quality of research work was very competitive with available human and financial resources. The faculty members and research students were publishing their research papers in reputed journals. The best practice was that the senior faculty members were very supportive to younger faculty members to create competitive knowledge.

The faculty members were also having collaborative research program with research laboratories in USA, Russia, Australia and European countries. In these days I also worked in Orsay, Canberra and Duisburg universities. There was nearly perfect ambiance of doing and learning science in these universities. The core courses were advanced and the students were involved in innovative instrumentation. The teaching and research ambiance in physics department was also competitive with above foreign universities in those days.

At the same time CSIR, DAE and other research institutions were also looking forward to collaborate in research projects of their interest in physics department. Therefore these institutions were also supporting the research projects of the department by providing financial assistance for research equipments, research personal and technical staff to accomplish the research project and to upkeep the research laboratories. In this process the department was getting enough grants from UGC, CSIR and

DAE for scientific dynamics of the department.

The department was well recognized for its teaching and research activities in three major areas; Theoretical and Experimental Nuclear Physics, Particle Physics and Solid State Physics. There were also two important research sections of Atomic Spectroscopy and Geochronology. The seminars, symposium and workshops in nuclear physics, particle physics and solid state physics were regularly held. Figs. 3, 4 and 5 show the students observing the stars and celestial installations in night, students working in research laboratory trying to create new knowledge and students interacting in the poster session of the symposium.

This was very exciting environment for research work in the department. The department was also getting the special grants under Special Assistance Program (SAP) and Center for Advanced Studies (CAS) programs of UGC to increase the faculty strength to strengthen teaching and research laboratories. The teachers



**Figure 3**



**Figure 4**



**Figure 5**

and students were working till late in the evening, on weekends and even on holidays. This was the period when the department was growing fast upward.

The faculty strength became nearly forty-two which was evenly distributed in strength and in specialization in the major areas of academic activities. The faculty members were writing the research projects to generate resources for the academic dynamics of the department. The existing infrastructure facilities were being provided to young faculty members for their growth in research work in each group and to each individual.

The PhD students were moving to other universities and research institutions on teaching and research positions. Many students were going abroad for postdoctoral fellowship. This was very flourishing period for the research dynamics in the department. I also enjoyed working, contributing and getting encouraged.

### **Academic Eminence**

Prof. Yash Pal, former UGC Chairman, Prof. K.N. Pathak, and Prof. A.K. Grover, former Vice chancellors of Panjab University, Prof. Satya Prakash, former Vice Chancellor of Jiwaji University Gwalior, Dr. Manjit Singh, former Director TBRL, Chandigarh Dr. P.D. Gupta, former Director of RRCAT, Prof. A.K. Sood,

Principal Scientific Advisor to Govt. of India and Prof. Tankeshwar Kumar, Vice Chancellor of Central University, Mahendragarh, are few eminent Alumni of physics Department.

Prof. Satya Prakash, Prof. M.M. Aggarwal, Prof. S.K. Tripathi and Dr. Lokesh Kumar are included in Stanford University's list of "World Top 2% scientists based on career long data and / or single year impact 2020 and 2022. Prof. Jasbir Singh and Prof. Vipin Bhatnagar are among the top scientists according to DST report based on citations.

### Physics Association

This is the creativity platform of physics students. They write essays on contemporary topics of physics, hold debates, organize cultural activities, and hold outdoor and indoor sports competitions and so on to explore other dimensions of talent of physics students. The spectacular dance show of physics students is shown in Fig.6



**Figure 6**

### Differentiation

Yes, with the implementation of rotation of Headship and Merit Promotion Scheme some aberrations erupted in but still the sizable strength of faculty members continued their spirit of commitment and dedication for quality

teaching and research. The national and international research collaboration programs continued.

With the implementation of reservation policy religiously the difference in the adoptability of course contents among students became visible. As the students cannot be retained due to fix number of intake of new students the course contents of HS were reorganized that all the students get their degrees within the stipulated time. The competitive graduation system of BSc (HS) and MSc (HS) got changed.

When these students joined PhD program, it was hard to train them to achieve the international competitive level of research particularly in physics within a period of 3-4 years to create significant new knowledge. This affected the contents of PhD thesis and the quality of publications.

With the implementation of roster system of appointment most of the posts remain vacant due to nonavailability of qualified faculty members. Further with the retirement of senior faculty members the faculty strength reduced to nearly half the strength that of the sanctioned posts. The guest faculty is accomplishing the obligatory duty to teach the students in the class rooms and laboratories. But it does not bring in the teacher – taught relations of mutual confidence to learn and to create knowledge. Now a lecturer is sure to be professor within a span of minimum time period. This may dilute the competitive academic ambiance; may be an unhealthy index for academic institution.

The author is thankful to Prof. G.S.S. Saini and Mr. Lokesh Kumar for their kind help.

**PROF. SATYA PRAKASH**

# TRANSFORMATIVE JOURNEY OF ARTIFICIAL INTELLIGENCE

Garima Joshi, Renu Vig

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## Abstract

Artificial intelligence has come a long way in last seventy five years. This article looks at how AI has changed over time, explaining advances in logic, probability, systems theory and neural computation that have helped build intelligent devices. It highlights major milestones and the contributions of key pioneers who connected theoretical principles with practical engineering. It also highlights landmark achievements and innovations that have impacted society and industry. The article illustrates how insights from physics and neuroscience have shaped the learning and training processes of computational models. In addition to tracing the technical evolution, it examines AI's broader societal influence across healthcare, education, communication, industry, and arts. While the technology is already transforming these domains, its long-term consequences will become evident only over time. We need to ensure appropriate policies exist so that society can benefit from these advancements.

**Keywords:** Artificial Intelligence (AI), Machine Learning (ML), Neural Networks, Deep Learning

## 1. Introduction

Artificial intelligence (AI) and machine learning (ML) came into existence through a combination of several disciplines like computer science, mathematics, physics, and neuroscience. Initially, AI was all about following rules and logic, but today algorithms can retrain and generalize, using structures like neural networks and deep learning (Ball, 2019). These new approaches are capable of handling complicated jobs involving vision, understanding language, and making decisions.

Ideas from physics and neuroscience have been helpful in creating models for learning and cognition. Neurobiological discoveries have driven AI research beyond rule-based approaches toward the development of systems inspired by the structure and functioning of the human brain (Barbierato, 2025). For instance, artificial neural networks (ANNs) mimic interconnected "neurons" and synapses. They can store and recall

information much like our own memories, using principles from physics and neurobiology that describe how systems settle into stable states (Boden, 2018).

Neuroscience has given us a better understanding of how our brains process information efficiently. Findings from studying individual neurons and neuroimaging have supported hypotheses like efficient coding, which states that early sensory systems minimize redundant neural firing while maximizing information transmission. Learning methods inspired by biology, such as Hebbian learning (which suggests that when neurons fire together, their connection gets stronger), are key to many models for memory, recognizing patterns, and making associations (Cath, 2017). The emphasis on neurobiological plausibility has encouraged researchers to develop bottom-up models that aim to capture not only cognitive

functions themselves, but also the ways in which these functions could arise from interacting networks of neurons (Domingos, 2015).

Statistical physics and theory of dynamical systems have contributed foundational principles to understanding learning and cognition. The concept of spin glass models, long studied in physics, helped shape early theories about how neural networks store many patterns and deal with noisy or partial inputs (Durrani, 2024). Hopfield’s models and later Boltzmann machines took inspiration from physics using energy functions and concept of free energy to describe network behavior (Dwivedi, 2023). Another significant direction is the development of physics-informed neural networks (PINNs), which incorporate physical laws, often written as differential equations, directly into the training process to ensure that the resulting models satisfy known constraints (Taddeo and Floridi, 2018).

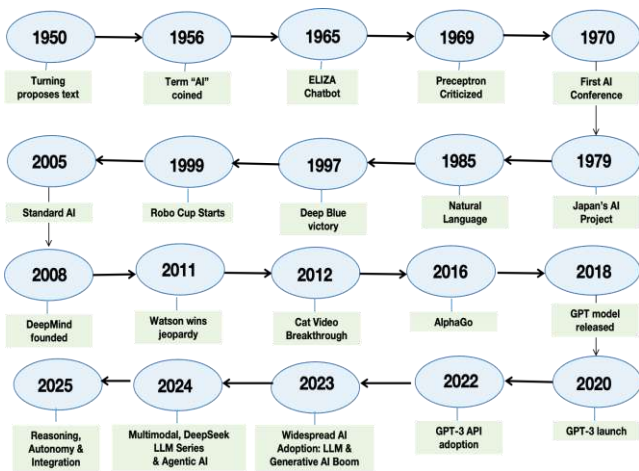
(Fu, 2024).

Figure 1 shows development of AI through distinct stages, with each phase bringing together theoretical insights and practical engineering (Gerdon, 2022). The evolution of AI is therefore more than a record of algorithms but a story of scientific curiosity, interdisciplinary collaboration and transformative potential that continues to redefine the limits of machine capability (Grzybowski, 2024). The 2024 Nobel Prize in Physics honored neural network research, underscoring deep connection between physical theory and computational intelligence (Grace, 2018). The article also addresses current challenges and future directions, emphasizing the need to balance innovation with ethics, transparency and human-centered design.

## 2. Tracing the Arc of AI

### 2.1 Laying the Foundations and Symbolic AI (1950s-1970s)

Back in 1950, Alan Turing surprised everyone through a paper called "Computing Machinery and Intelligence," asking that big, enduring question: "Can machines think?" He came up with this idea for an "imitation game," which is popularly known as the Turing Test, provided a criterion for assessing machine intelligence. Even more remarkably, Turing envisioned machines that could learn as they went along, basically setting up the whole philosophical and computing basis for AI research (Alufaisan, 2021). Then, in 1956, the Dartmouth Conference, spearheaded by John McCarthy, Marvin Minsky *et al.*, officially made AI as a field of study. This era was all about symbolic AI, expert systems, and creating programming languages like LISP (List Processing). Arthur Samuel's checkers program also showed off the idea of algorithms that could

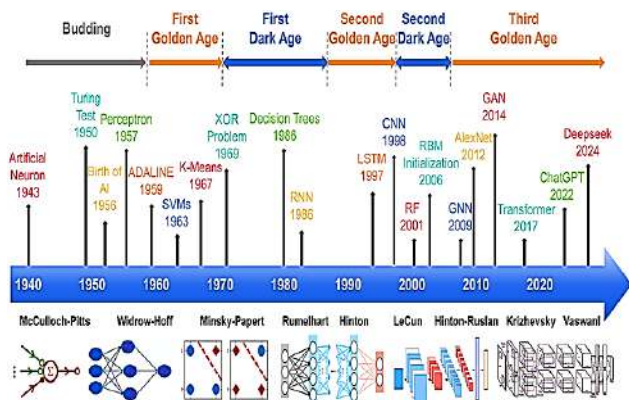


**Fig 1: Evolution of AI**

Recent research has also drawn on concepts from statistical physics and phase transitions to better understand what makes neural networks generalize effectively, how their internal representations evolve, and how learning systems balance trade-off between stability and flexibility

learn themselves, even coming up with the term "machine learning" and primarily laying early foundations for data-driven approaches (Jiang and Wang, 2018).

Then, in 1958, Frank Rosenblatt created the Perceptron, which was the very first ANN that could do simple pattern recognition. Although limited in scope, it demonstrated potential of biologically inspired computation (Jordan and Mitchell, 2015). Concurrent developments in heuristic programming and expert systems started pushing AI into real-world uses like medical diagnoses and engineering, giving us the first real glimpses of machine intelligence in action (Kaplan and Haenlein, 2019).



**Fig 2. Key Algorithms and Techniques in AI and ML (Yu, 2025)**

## 2.2 The AI Winter and Revival (1970s-1990s)

Things got off to a hopeful start with AI in 1950s and 60s, but by the mid-70s, it hit its first "winter." Basically, researchers were very excited about what the technology could do, but enthusiasm outpaced what the technology could deliver. Problems with symbolic AI systems, especially neural networks like perceptrons, became clear. For instance, what single-layer networks could actually compute was pretty limited. Hence, both funding and interest took a nosedive (Lavazza, 2025). Then, in early 80s,

there was a revival led by expert systems, which used rule-based logic to encode expert knowledge for specific domains such as medicine and configuration system. These used logic rules to capture what experts knew about specific areas like medicine or setting up systems. They proved that AI could actually be useful, even if only for very specific tasks.

However, by late 80s and into 90s, expert systems started showing their weaknesses. They were often fragile, costly to keep running, and difficult to expand. Simultaneously, advances in algorithms and increased computing power revived neural network research. The development of the backpropagation algorithm by Hinton, Rumelhart, Williams *et al.* made it much easier to train neural networks with multiple layers. On top of that, machine learning techniques such as decision trees and support vector machines became more feasible and widely used. This combination of better ideas, more data, and robust hardware paved way for major advancements in the deep learning era that came next (Grzybowski, 2024).

## 2.3 Rise of Machine Learning and Neural Networks (1990s-2010s)

During 1990s into 2000s, machine learning and neural network research resurged and began transforming many fields. Systems could now automatically learn useful features from data, rather than relying entirely on handcrafted rules. A landmark event illustrating growing capabilities was IBM's Deep Blue defeating Garry Kasparov in chess in 1997, becoming the first computer to win a full match against a reigning world champion. Another milestone came in 2016, when Google DeepMind's AlphaGo beat Lee Sedol in ancient game of Go, a game considered far more complex for computers

due to its large search space and intuitive reasoning requirements. At the same time, increases in computational power, larger datasets (“big data”), and advances in cloud computing infrastructures provided the tools needed to train deeper models and scale them practically. These combined developments laid foundation for deep learning revolution that dominated AI research in 2010s (Jiang and Wang, 2018).

Deep learning reshaped AI research and applications. Geoffrey Hinton, Yann LeCun, and Yoshua Bengio are designated as the “Godfathers of Deep Learning” for developing methods for training large-scale neural networks. LeCun’s convolutional neural networks (CNNs) transformed image recognition, Bengio advanced deep generative models, and Hinton contributed innovations in representation learning. Parallel efforts by Andrew Ng and others popularized ML education and established large-scale research initiatives such as Google Brain, accelerating global adoption of AI techniques (Lavazza, 2025).

#### **2.4 Modern AI and Deep Learning (2010-2024)**

Since the 2010s, AI has taken huge steps forward due to deep learning and massive neural networks, which have changed how machines can understand and perform tasks. Large Language Models (LLMs) like BERT and GPT-3, which are built on transformers, have dramatically improved how well computers can grasp human language and create text, making conversational AI much smoother, more aware of context, and genuinely helpful. Examples of other LLMs include T5, RoBERTa, and more recent models like Claude, Gemini, and those from the Llama family.

Reinforcement learning has also seen significant progress, enabling AI to get really good at tricky

jobs like playing games, controlling robots, and making choices in changing situations. At the same time, fields like healthcare, finance, and transportation have been using newer AI tools widely. For instance, AI is now being used for treatments tailored to individuals, spotting fraud, self-driving cars, and making supply chains run better. Key breakthroughs include AI-driven scientific research like protein structure prediction and climate modeling, improved medical diagnoses and treatments, more sophisticated image and video generation, and highly capable robots. All these advancements together have led to AI era, bringing both exciting possibilities and fresh challenges. The way AI brings together different fields really shines through in the work of John J. Hopfield and Geoffrey E. Hinton. Hopfield’s associative memory networks showed how ideas from statistical physics could be used to model human brain. Hinton deployed concepts from statistical mechanics in machine learning to make these algorithms more efficient. Their groundbreaking research on neural networks, which allows machines to recognize patterns and learn adaptively, earned them the 2024 Nobel Prize in Physics (The Nobel Prize, 2024).

#### **2.5 AI Advancement**

AI systems are designed for specific tasks like playing chess or recognizing faces. However, Artificial General Intelligence (AGI) would be a versatile “generalist” that can transfer learning across different domains and adapt to new situations. There is a strong drive in AI to create AGI systems that can take smart decisions. These systems often borrow ideas from how working of human brain and include safety features that are tested appropriately. Scientists are putting together huge systems with designs that mimic

the brain or are a mix of different approaches, adding in basic safety measures that are tested in real situations (Le Cun et al., 2015). A cool idea in this field is "sentinel agents." These are special AI agents that keep an eye on how other agents in a system are acting, looking for any bad behavior and making sure things are reliable and trustworthy. For example, a system could use sentinel agents to watch over how agents talk to each other, spot possible dangers, enforce privacy and access rules, and keep detailed logs of everything. Working alongside these sentinel agents are coordinator agents. They make sure policies are followed and manage agents, adjusting those policies based on warnings from the sentinel agents to keep the whole group of agents working properly (Ooi, 2025).

Evaluating the performance of autonomous AI systems requires assessment criteria that extend beyond conventional metrics such as task accuracy and execution speed (Schmidhuber, 2015). A comprehensive evaluation framework should encompass five key dimensions: functional capability and performance, robustness and adaptability, safety and ethical compliance, human-AI interaction, and economic viability. To support assessment across these dimensions, novel evaluation metrics proposed (Siebert, 2021). Evidence from real-world industrial deployments indicates that, although AI systems can substantially increase productivity, critical factors such as fairness, trustworthiness, and long-term sustainability are often overlooked. This underscores the need for multidimensional evaluation approaches that integrate automated performance metrics with human-centered assessments and financial reviews to ensure the responsible and sustainable use of AI systems (Brewka, 1996).

### 3. Current Challenges and Debates

As AI systems become advanced, it is imperative to address issues such as algorithmic bias, transparency in decision-making processes, and societal impacts of AI deployment to ensure that these technologies align with human values (Taddeo and Floridi, 2018). Lately, conversation around AI has shifted to include more technical, ethical, and political concerns (Tai, 2020).

With AI getting stronger, there has been a tug-of-war between better power like faster models, enhanced automation, better performance and accurate AI behaviour and safety (Taddeo and Floridi, 2021). Many experts believe alignment and safety are not in pace with speed of capability development. For example, there is increasing attention on risks that appear after AI systems are deployed, factors like self-improvement, multiple agents working together, or unexpected behaviors that emerge over time (Kaur and Sharma, 2024). Economically, forecasts suggest that while AI may bring big productivity gains, it could also displace many tasks and jobs, so it is crucial to consider how to retrain people and share the gains equitably (Voigts *et al.*, 2024). Generative AI, specifically, has sparked debates about fairness, copyright, data privacy, model transparency and accuracy in systems behaviour which do not always match statistical fairness metrics (Xie *et al.*, 2025).

As a response, policy reports and scholars are advocating for better structural and governance tools. For instance, India's Reserve Bank has proposed a framework for responsible AI in its financial sector, called FREE-AI, which emphasizes risk management, indigenous model development, audit frameworks, and oversight (Mathew *et al.*, 2020). Worldwide, reports like the AI Governance International Evaluation Index

(AGILE Index, 2024-2025) are measuring how countries are doing in AI governance highlighting gaps in regulation, standards, certification and comparing how prepared different countries are (Zuboff, 2015). Governments and organizations are increasingly calling for “governance by design”: building in ethics, human oversight, transparency, and safety constraints into AI systems from the start rather than as afterthoughts. Still progress remains uneven: many AI projects lack strong oversight, accountability mechanisms, or real capacity for enforcing ethical or safety measures.

#### 4. Impact of AI in Various Sectors

As we know, AI has impacted every field, making systems efficient, easier, and tailored. AI is changing every aspect of our lives, bringing both exciting possibilities and tricky challenges.

- In medicine, AI helps doctors spot diseases early, come up with patient specific personalised treatments, and handle patient records smoothly. AI is facilitating better treatment plans. AI programs help with learning and helping medical students practice with virtual scenarios and learn at their own pace.
- For schools, AI tools can create learning experiences that fit each student, give tests that adjust to their level, and automate a lot of the administrative work, making education more welcoming and effective for everyone. AI is helping to tailor lessons to each student, give instant feedback, and teach kids about AI itself.
- The way we communicate has also improved because of AI through enhanced language translation, sentiment analysis, and automated content creation, which helps

break down language and culture barriers.

- Industries leverage AI for predictive maintenance, supply chain optimization, and data-driven decision-making, pushing them to be more innovative and competitive. It is also transforming human-technology communication methods, notably through virtual helpers and chatbots. Industry 5.0 shifts the focus from Industry 4.0’s efficiency-driven automation to a value-driven approach centered on human-machine collaboration, prioritizing the well-being of the worker and leveraging human creativity alongside technology
- Even in arts, AI is helping people create new content, music composition, and visual art generation, opening up new creative avenues and challenging traditional artistic boundaries. Research shows AI is shaking things up in how art is made, how we interact with tools, and how different fields come together. It’s opening up new ways to do visual art and using data to come up with fresh ideas in design and art studies.

All these developments illustrate how important AI is in creating a world which is better connected, runs smoothly, and is full of new ideas. Though benefits are substantial, there are recurring concerns: possible displacement of jobs, bias in algorithms, ethical and privacy risks, and need to ensure fairness and human well-being are part of deployment decisions.

#### 5. AI Transformation of Panjab University

Panjab University (PU) has embarked on a profound strategic initiative, to reposition itself for research and development in Artificial Intelligence (AI). This concentrated effort is

driven by a commitment to establishing robust high-performance computing (HPC) infrastructure, for advanced skill development, and fostering translational DeepTech innovation. The goal is to provide students and researchers with the necessary resources for groundbreaking work in these rapidly evolving fields.

The cornerstone of this initiative is the recent inauguration of a cutting-edge AI Data Centre, established through a substantial Corporate Social Responsibility (CSR) contribution, alongside activation of the Intel Unnati Lab. This multidimensional infrastructure approach immediately positions Panjab University at the forefront of AI based education in this region. The translation of academic research into

commercially viable products is managed through established institutional frameworks as shown in Table 1.

Panjab University's approach integrates infrastructure with human capital development, particularly through faculty enablement programs and AI based curriculum delivery. Institutional frameworks such as the Technology Enabling Centre (TEC) and CIIPP facilitate technology transfer and commercialization, supporting over 200 industries and launching DeepTech startups. Strategic CSR funding further enhances AI-driven materials analysis and prototyping, aligning Panjab Universities' capabilities with national industrial goals.

**Table 1 : Strategic Alignment: PU Initiatives and Industry/Research Outcomes**

| <b>Initiative/Facility</b>       | <b>Primary Purpose</b>   | <b>Measurable Outcome/Impact</b>  |
|----------------------------------|--|---|
| Design Innovation Centre         | Design-centered synergy catalyzed for a variety of technology-driven projects around a plethora of ideas | Established 6 different Labs and Developed more than 110 prototypes, 16 patents and 10 startups   |
| AI Data Centre                   | Large Model Training, Deep Learning  | Provides critical high-performance computing capabilities, enabling industry-relevant research and custom model training with approximately 64.8 TFLOPS of compute performance. |
| Intel Unnati Lab                 | Faculty/Student Skill Enhancement  | Standardized curriculum delivery; focus on edge AI optimization and industry skill gap reduction.   |
| SAIF/CIL Integration             | Materials Analysis & Prototyping   | AI-driven quality control; accelerates new material development and industrial applications.  |
| PU Incubation Centre (CIIPP/TEC) | Commercialization of DeepTech  | Successful launch of high-impact, industry-specific startups (e.g., Dach Biotech, Terafac)  |

## 6. Conclusion

At the pinnacle of this technological revolution, a profound responsibility emerges to navigate the persistent, complex challenges of interpretability, bias, and sustainability while upholding core ethical principles. The "black box" nature of many computational models raises significant concerns about trust and accountability, particularly when AI-driven decisions impact human lives in high-stake domains like healthcare, finance, and criminal justice. Furthermore, without deliberate intervention, existing societal biases can become ingrained in training data, perpetuating and amplifying unfair outcomes that exacerbate inequalities. This must be coupled with addressing the substantial energy consumption and resource demands of large-scale AI, a critical sustainability challenge. The path forward demands an unwavering commitment to transparency, ensuring stakeholders can understand and audit how and why AI systems reach their conclusions. It necessitates robust accountability frameworks that define responsibility for the consequences of AI's actions. Ultimately, the goal is to align future AI advancements with human-centered values, guaranteeing that technology augments rather than undermines human dignity, fairness, and overall well-being. This is not merely a technical task, but a societal imperative to build a future where AI serves as a responsible and trustworthy partner to humanity.

Panjab University's strategic investment in AI infrastructure, skill development, and translational research has yielded a robust ecosystem for DeepTech innovation. The success of startups underscores the university's capacity to convert scientific research into impactful industrial applications. Looking ahead, PU aims

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to scale its incubation model by expanding shared compute access and prioritizing support for ventures developing complex AI systems, including domain-specific LLMs and robotics platforms. This forward-looking plan positions PU not only as a leader in academic AI research but also as a catalyst for industrial transformation, contributing meaningfully to India's vision of Viksit Bharat@2047.

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# CENTURY OF THE PUNJAB SCHOOL OF MATHEMATICS

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## Abstract

The Punjab School of Mathematics, whose origin lies in the vibrant intellectual milieu of pre-partition Lahore, has completed a hundred years of remarkable contribution to number theory and related fields. This article presents a comprehensive account of its evolution, from the pioneering work of Sarvadaman Chowla—its true nucleator—to the foundational contributions of Hansraj Gupta and the enduring legacy of Ram Prakash Bambah, who left us just four months before his 100th birthday. Drawing upon archival sources and recent scholarship, the article traces the School's development through the turbulent mid-twentieth century, its re-establishment at Panjab University, Chandigarh, and its rise to national prominence as a Centre for Advanced Study in Mathematics. It highlights the School's rich research culture, its collaborations with global luminaries, and the significant achievements of successive generations of mathematicians, including several distinguished women scholars. By documenting this century-long journey, the article seeks not only to honour the architects of the Punjab School of Mathematics but also to underscore its continuing influence on the landscape of mathematics and beyond.

## Introduction

It is a moment of reflection that the centenary of the Punjab School of Mathematics coincides with the birth centenary of one of India's most distinguished mathematicians, Professor Ram Prakash Bambah (1925–2025). His passing away earlier this year lends a solemn dimension to the celebrations, providing an occasion not only to honour a century of mathematical excellence at Panjab University<sup>1</sup> but also to commemorate the extraordinary life and legacy of Professor Bambah, together with Professors Hans Raj Gupta and Sarvadaman Chowla, whose pioneering contributions laid the very foundations of the

'*Punjab School of Mathematics*'. In this article, our focus will primarily be on these legends.

As we reflect on this remarkable century, it is imperative to highlight the way Punjab has secured a legacy that resonates across the Indian and global mathematical community. The ongoing legacy of this tradition is meticulously documented in Purabi Mukherjee's book *Research Schools on Number Theory in India* published by Springer (Mukherjee, 2020). The book positioned the Punjab School prominently on the international stage, surpassed in recognition only by the globally renowned South Indian School, whose origin is associated with the iconic genius Srinivasa Ramanujan

<sup>1</sup> The name and location of this university have undergone various changes throughout its history, most notably as the University of the

Punjab at Lahore and later as Panjab University, Chandigarh (see Sethi et al. 1968). We will use the common abbreviation **PU** to refer to all these incarnations.

(1887–1920), the likes of whom are born very rarely, even in a millennium. The *Punjab School of Number Theory*, which was initiated in Lahore, evolved into the *Punjab School of Mathematics* in post-independence era at Chandigarh.

### 1. Sarvadaman Chowla: The Nucleus of the Punjab School



#### Professor Sarvadaman Chowla

After Ramanujan's passing away in 1920, the school at Madras was continued by Anand Rau, who also earned a Ph.D. with G. H. Hardy and was a contemporary of Ramanujan at Cambridge. The nucleator of the Punjab School at Lahore was undoubtedly Sarvadaman Singh Chowla alias Sarvadaman Chowla (1907–1992), whom Wikipedia refers to as an *England-born American mathematician of Indian origin*.

#### 1.1 Early Spark and Cambridge Sojourn

Sarvadaman, nicknamed Servi, was born to Mrs. Shakuntala and Bhai Gopal Singh Chawla, M.A. (Mathematics) of Government College Lahore (GCL). The latter was on a two-year study leave (1906–08) from GCL to Trinity College, Cambridge. After his return to Lahore, he was promoted to Professor of Mathematics in 1910. Servi was born in England in 1907.

Bhai Gopal Singh Chawla was among the first cohort of Indian educators in government colleges in colonial India who were deputed for studies

abroad under a scheme introduced in the wake of the Indian Universities Act of 1904, a common Act for the then five Indian universities at Madras, Allahabad, Bombay, Calcutta, and Lahore. Notably, Panjab University, Chandigarh, in independent India, continues to operate under a modified version of that same 1904 Act.

The remarkable mathematical ability of B.A. student Servi started to get noted nationally, as he commenced providing solutions from 1925 onwards to the mathematical problems presented in the *Journal of the Indian Mathematical Society* (JIMS, in publication since 1910). In 1925 and 1926, he published eight papers in JIMS, which included the solution to a question due to Ramanujan and three questions posed by the mathematics teacher, Principal Hem Raj Gupta of Dyal Singh College, Lahore, in the same journal in 1924.

Servi completed his M.A. from GCL in 1928, and by the end of 1929, he had published 18 mathematical notes and original papers in JIMS. Father (GSC) and son (Servi) had both participated in the Annual Meeting of the Indian Mathematical Society held in December 1928, where Servi gave talks on three of his latest papers published in JIMS to his peers from the rest of India. The senior Chowla (GSC) also had a separate publication in the 1928 issue of JIMS. The name of Servi had appeared in JIMS for the first time in 1924, when he posed two mathematics problems in it (see Huard et al. 1999 and Chowla, 1924). Servi had built up a reputation as a college student for having a special ability to provide solutions to problems due to Ramanujan; in all, he solved 34 problems posed in JIMS between 1925 and 1931.

Bhai Gopal Singh had accompanied his son for admission as a Ph.D. student at Trinity College, Cambridge in 1929, unfortunately he himself

succumbed to pneumonia while travelling in Europe in December 1929 (see Sinha, 2023). Luckily, S. Chowla did not abandon his studies at Cambridge; his housemate during his sojourn (1929–31) was the Lahore-born Subrahmanyam Chandrasekhar (1910–1995), son of C. S. Ayyar, elder brother of the would-be Nobel Laureate (1930) in Physics, C. V. Raman. Chowla and Chandrasekhar maintained life-long correspondence with each other.

Chowla had enrolled for Ph.D. under the supervision of J. E. Littlewood, with whom Ramanujan had also interacted during his stay at Cambridge while working with the distinguished mathematician G. H. Hardy during 1914–19. Chandrasekhar's Ph.D. supervisor at Cambridge was R. H. Fowler, with whom Homi Bhabha and D. S. Kothari also worked as doctoral students immediately after Chandrasekhar. Chen-Ning Yang and Tsung-Dao Lee were once the only two students in a graduate course taught by Chandrasekhar at University of Chicago (see Johnson, 2025). These two students were awarded the Nobel Prize in 1957, whereas their teacher, S. Chandrasekhar, was honoured with the Nobel Prize in Physics in 1983 for ideas he had propagated at Cambridge in the 1930s.

Chowla completed his Ph.D, titled *Contributions to the Analytical Theory of Numbers*, within just two years at Cambridge. His friend Chandrasekhar obtained his Ph.D. a little later in 1933. In 1934, Sir C. V. Raman included both Chandrasekhar and Chowla among the sixty-five scholars who initiated the Indian Academy of Sciences as founding members.

## 1.2 Teaching and Collaborations in India before Independence

After returning to India in 1931, Chowla took up

his first teaching position at St. Stephen's College, Delhi. There he married a Bengali Brahmo, Himani Majumdar, younger sister of political activist Sucheta Majumdar (later Kriplani), who went on to become independent India's first woman Chief Minister of Uttar Pradesh (1963–67).

Dr. Sarvadaman Chowla moved from Delhi to Banaras in 1932 as Lecturer in Mathematics at Banaras Hindu University (BHU), on the invitation of Pt. Madan Mohan Malaviya (founder of BHU), to fill the vacancy created by the departure of polymath D. D. Kosambi to Aligarh Muslim University (AMU) at the inducement of Professor André Weil, Chair Professor of Mathematics there. While at BHU, Chowla met the young French mathematician André Weil, later to become one of the most impactful mathematicians of the 20<sup>th</sup> century. He had returned to Europe after a two-year stay in India. André also co-founded, with a few others, the famous Bourbaki group of mathematicians in France. Another legendary mathematician of India, Harish Chandra (1923–1983), is known to have been influenced by the Bourbaki School. Harish Chandra had commenced research under Homi Bhabha at Indian Institute of Science, Bangalore (IISc) in 1944 after his M. Sc. in Physics from University of Allahabad. Bhabha sent him to work with Nobel Laureate Paul Dirac at Cambridge as he moved to Bombay (now called Mumbai) to establish Tata Institute of Fundamental Research. Harish Chandra obtained his Ph.D. in 1947 working on *Infinite Irreducible Representations of Lorentz Groups* at Cambridge. He later became a Professor of Mathematics at the Institute of Advanced Study Princeton, USA, where Chowla also moved in 1948 after the partition of India. Harish Chandra had been short listed for the coveted Fields Medal in Mathematics

in 1958. Both Chowla and Harish Chandra received Padma Bhushan from the Government of India after independence.

Chowla had stayed at BHU for only one year. Dr. Sarvepalli Radhakrishnan, the second Vice Chancellor of the newly established Andhra University, Waltair, appointed him as a Reader and the Head of Department of Mathematics at the suggestion of his friend Chandrasekhar, who had declined the same position offered to him first. It may be pointed out that Dr. Radhakrishnan later became the President of India in 1962.

Nobel Laureate Sir C. V. Raman had moved from Calcutta to accept Directorship of IISc Bangalore in 1934. A year later, he invited his nephew Subrahmanyam Chandrasekhar to join him as a faculty member at IISc, but his father persuaded him not to accept the offer. Chandrasekhar, in turn, is believed to have suggested Chowla's name to his uncle, but in vain. Chowla had described his isolation as a mathematics researcher at Waltair to his friend Chandrasekhar some months earlier.

After spending three years (1933–35) at Waltair, Chowla had the opportunity to return to Government College, Lahore—his alma mater—as Professor of Mathematics in 1936. Professor J. E. Littlewood, Fellow of Royal Society, England described him as the “*most promising Indian mathematician Cambridge has had since the war*”, while supporting his candidature at the University of the Punjab, Lahore (see page 6). Professor Sarvadaman Chowla was inducted into the Indian Education Service while at Lahore in 1939.

At Waltair, Chowla's teaching at the postgraduate level had inspired the young C. R. Rao (1920–2023), who progressed to become a *living legend* in independent India first, and in the United States later, after superannuation from the Indian

Statistical Institute (ISI), Kolkata in 1982. Chowla authored a series of research papers with C. R. Rao in the 1940s, when the latter was at ISI, Calcutta. C. R. Rao was honoured with the Padma Bhushan in 1968. He was honoured with the U.S. National Medal of Science in 2001, India Science Award in 2010, and the International Prize in Statistics in 2023, a few months before his passing at the age of 102.

Chowla maintained his collaborations with the native mathematicians of the South Indian School throughout, as they spread out to different institutions across colonial India wherever jobs became available. The most notable of his collaborators before independence was S. S. Pillai (1901–50), with whom he maintained mathematical correspondence for two decades until Pillai perished in a plane crash in Egypt on his way to the Institute for Advanced Study at Princeton (Sury et al. 2012). Chowla also co-authored papers with K. Anand Rau, S. Sastry, R. C. Bose, T. Vijayaraghavan, D. B. Lahiri, et al., before independence (cf. Mukherjee, 2020).

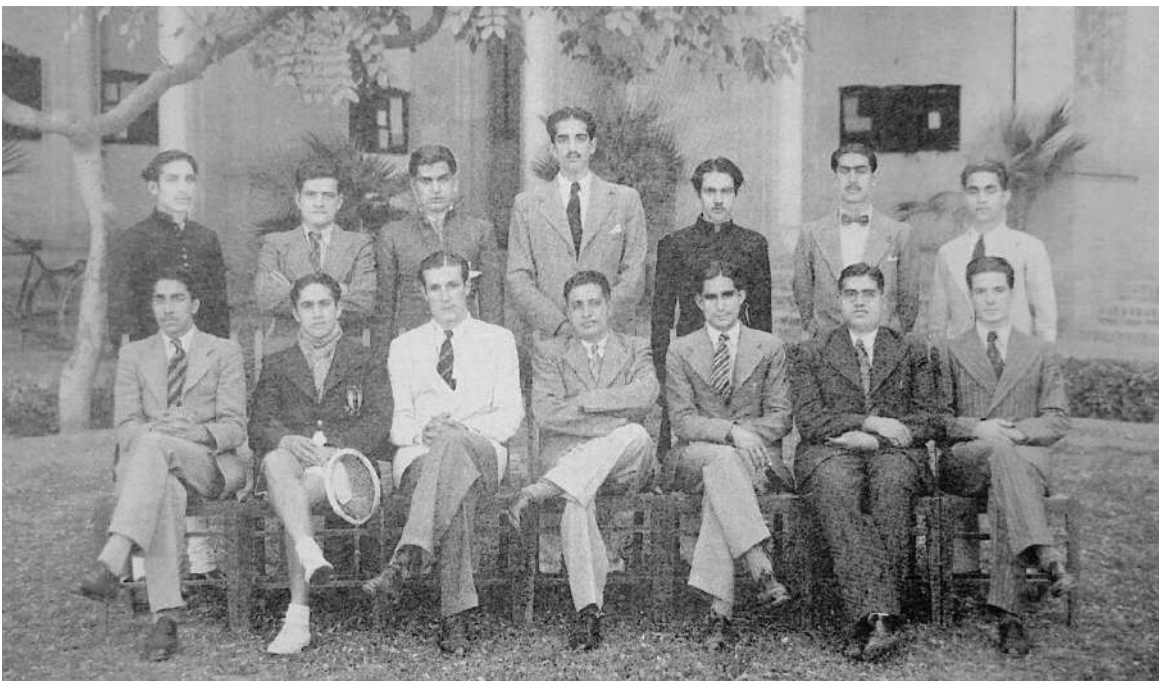
### 1.3 Nurturing the Next Generation at Lahore

At Lahore, the first research student of Chowla was the would be theoretical physicist Faqir Chand Auluck (FCA), the topper of 1934 M.A. (Mathematics) examination and was working as a temporary lecturer on leave vacancy to teach Mathematical Physics to M.Sc. students. FCA wrote numerous papers in Number Theory, working with Chowla as well as alone. While teaching at PU (1935–37) and Dyal Singh College, Lahore (1938–42), FCA came in contact with physicists Dr. P. K. Kichlu and Dr. D. S. Kothari (both former students of Professor Meghnad Saha at Allahabad University). FCA had also started to work on issues in Astrophysics and Statistical Physics at Lahore. Kothari later served as the

Scientific Advisor to the Ministry of Defence during 1948 to 1961 and as the Chairman of the University Grants Commission during 1961-1973. Kothari had also been selected to initiate the Department of Physics of Delhi University (DU) and he offered FCA a teaching position in 1942 to teach Mathematical Physics there. FCA earned Ph.D. in Physics from DU in 1943, and he was also awarded D.Sc. in Mathematics by PU in 1945. Along with FCA, S. Chowla's younger brother Inder Chowla also worked on several important problems in Number Theory, both with him and independently. Inder went on to obtain a Ph.D. in Mathematics at Cambridge with H. Heilbronn in 1942. Unfortunately, he passed away at a very young age in 1943.

Hans Raj Gupta, Daljit Singh, Abdul Majid Mian, Raj Kumar Talwar, Ram Prakash Bambah, Jagdish

Chandra Luther, Mahendra Raj, Abdus Salam and Fakir Chand Kohli were some noteworthy collaborators and students of Chowla at Lahore. Hans Raj (1902–1988), in fact, studied under his father as an M.A. student of GCL during 1923–24. Bambah topped the M.A. (Mathematics) examination with 600 out of 600 marks in 1945. Abdus Salam was one year junior to him and bettered Bambah's performance in all previous examinations other than M.A. examination. Salam provided an elegant new solution to a problem due to Ramanujan, posed to B.A. students by Chowla, and the latter himself proceeded to get it published in the journal *Mathematics Student* in 1943 in the name of Abdus Salam (cf. Aravinda et al. 2020). Salam proceeded to study at Cambridge in 1946 through a grant made available by a new NGO in Punjab. In 1979, Abdus Salam was honoured with the *Nobel Prize* in Physics.



*S. Chowla (seated, centre, front row) with students and colleagues at Government College , Lahore in the early 1940's. Source: ICTP Library*

Fakir Chand Kohli and Ram Prakash Bambah were both honoured with Padma Bhushan in

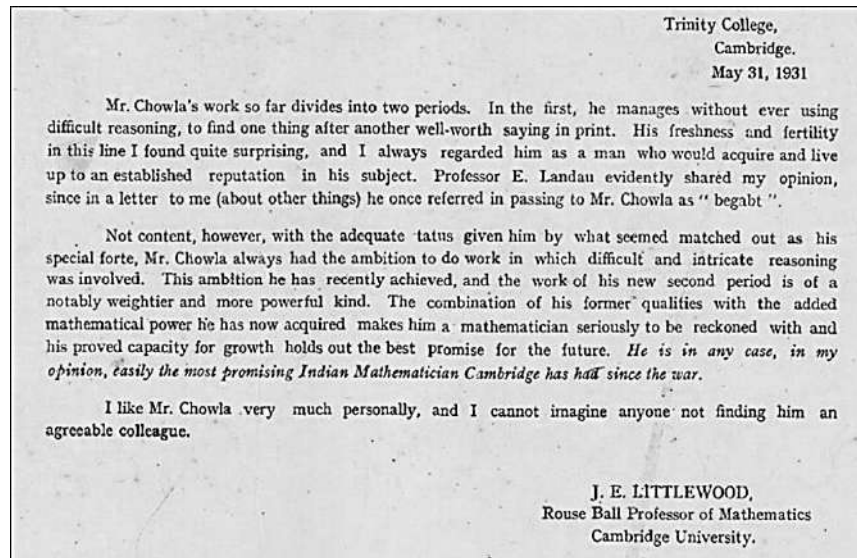
independent India. The latter had progressed to become the Vice Chancellor of Panjab University, Chandigarh from 1985 to 1991. However, he had needed help from his teacher Chowla to get his first teaching appointment. There was a moratorium on hiring in government jobs in Punjab soon after the second world war. Chowla, therefore, had to arrange for Bambah a stopgap assignment to teach Mathematics at Government College at Hoshiarpur, where Hans Raj Gupta was the Head of the Department of Mathematics. Bambah returned to Lahore to work as a research assistant to Chowla, and together they wrote 15 papers between April 1946 and February 1947. Thereafter, due to impending Partition of India, Bambah moved to Delhi to accept a leave vacancy position in lieu of F. C. Auluck, to teach Mathematical Physics to M.Sc. students at Delhi University. Dr. Auluck had proceeded on three years study leave to accept Senior Fellowship of National Institute of Sciences. Coincidentally, Dr. P. K. Kichlu had also left Lahore in January 1947 to join the Physics Department of Delhi University.

F. C. Kohli went on to become a co-founder and the first Chief Executive Officer (CEO) of Tata Consultancy Services (TCS). Raj Kumar Talwar later served as the Chairman of the State Bank of India. Jagdish Chandra Luther went on to become the Deputy Governor of the Reserve Bank of India. Mahendra Raj progressed to become one of India's most influential structural engineers, the designer of iconic buildings, like Mumbai's Usha Kiran, Hall of Nations at Pragati Maidan in Delhi, and the Salar Jung Museum in Hyderabad. He also worked in collaboration with Le Corbusier on the planning of Chandigarh.

#### 1.4 From Post-Partition Struggles to Global Recognition

In July 1947, Chowla and his family were able to leave Lahore with the help of his wife's sister Sucheta Kriplani. Around this time, Chowla applied for a Senior Fellowship at the National Institute of Sciences in India, having already applied the previous year for a position at DU. Eminent mathematicians such as Mordell, Davenport, Littlewood, and Hardy wrote strong letters of recommendation for him. In one of them, Littlewood described him as "*the most promising Indian mathematician Cambridge has had since the war*" (see the picture below). Yet, despite such testimonials, Chowla, a professor from Lahore, was unable to secure a position in independent India.

At that time, universities had very few positions for faculty recruitment. Typically, in universities, there was only one professor in each department, who also served as its head. After independence, DU had no separate Department of Mathematics—mathematics professors were appointed only in the Department of Physics. Independent India was thus unable to accommodate many potential researchers in the basic sciences. To address this situation, the Government constituted the Radhakrishnan Commission on November 4, 1948 and Dr. Sarvepalli Radhakrishnan was appointed as its chairman (cf. Radhakrishnan, 1950). Evidently, S. Chowla could not wait for the recommendations of the committee to arrive. Had Chowla joined the Mathematics Department of Panjab University at Hoshiarpur, alongside Professor Bambah in 1950s, the academic history of this region might have been very much different.



*Recommendation from his Ph.D. advisor J.E. Littlewood*

In 1948, Professor Sarvadaman Chowla left Delhi on an official Government of India passport and joined a temporary lecturer position (supported by funds from India) at the Institute for Advanced Study in Princeton. There, he had world-famous number theorist colleagues such as Paul Turán, Carl Ludwig Siegel, Paul Erdős, and Atle Selberg. Thus began a new chapter for Chowla in the West. In U.S.A., he also worked at the University of Colorado and the University of Kansas. In 1963, he was appointed Research Professor at Pennsylvania State University, a position he held until his formal retirement in 1976. He continued research for a decade more.

During his long research career (1925–1986), he wrote 350 research papers and guided 25 Ph.D. students, including his own daughter, Promita Chowla. He collaborated with the leading number theorists of his era and wrote papers with about 60 co-authors. Numerous important theorems and results in mathematics bear his name. These include the Ankeny–Artin–Chowla congruence, Bruck–Ryser–Chowla theorem, the Chowla–Selberg formula, the Mian–Chowla sequence, and the Chowla–Mordell theorem. His collected

works and correspondence with other leading mathematicians were published in three volumes by the Université de Montréal, Canada, in 1999, comprising a total of 1,417 pages. They trace a journey that began in Lahore's classrooms and culminated on the world stage of mathematics. According to Ayoub et al., Chowla was regarded as "*one of the best known number theorists from India to follow in the tradition of Ramanujan whose fertile and creative imagination*" earned him the epithet "*poet of mathematics*" among his contemporaries (see Ayoub et al. 1998).

Atle Selberg recalled that the death of Mrs. Himani Chowla around 1970 was a great blow to Chowla. His later years, Selberg noted, were clouded by ill health, financial difficulties, and an unwise lifestyle, though he remained unfailingly generous. was advised to move to Wyoming, where a Hindu resident cared for him. Selberg observed that, despite little exercise, Chowla's rugged constitution carried him to a ripe age. He recalled an excursion on the Trail Ridge Road—over 13,000 feet high—where he had run ahead of the group. Selberg saw Chowla sprinting uphill without losing breath, and remarked that *beneath*

*his outlook there was hidden the makings of a Sikh*

## 2. Hansraj Gupta: Pioneer of Partition Theory



### Professor Hansraj Gupta

Chowla's key contribution at Govt. College Lahore was disproving a conjecture of Ramanujan. For this, he used the partition function tables published by Hansraj Gupta. This brought international recognition to Hansraj Gupta, who was born in Rawalpindi (now in Pakistan), then part of British India on October 9, 1902. His father, Jati Ram Gupta, served the then princely state of Patiala as a petty official.

Hansraj published a multi-year calendar during his school days (see pp. xvi–xvii, Hans-Gill, 2013). In 1923, it was displayed in London at the British Empire Exhibition, earning Hansraj a certificate of merit and a medal.

In the year 1925, Hansraj completed his M.A. with a high second division, ranking first in the university. After his M.A., however, he was jobless for a year and then worked at Sadiq Egerton College in Bahawalpur (now in Pakistan) for two years. In 1928, he joined as a mathematics teacher at Government Intermediate College, Hoshiarpur (GCH). In 1947, it attained the status of a degree college, and Hansraj Gupta was elevated to the position of Lecturer in Mathematics.

(see Huard et al. 1999 or Selberg 1995).

### 2.1 Early Education

After matriculating from University of Punjab at Lahore, in 1919, Hansraj Gupta passed the intermediate examination from Mohindra College, Patiala (MCP) in 1921, earning a first division and scholarships at both the school and college levels.

Hansraj Registered for M.A. in Mathematics at MCP which was affiliated with University of Punjab at Lahore. Since it lacked any formal teaching arrangements, Hansraj was not required to attend any classes, allowing him to complete it a year early. During 1924, he enrolled in the second year of his M.A. at Dyal Singh College in Lahore. The principal of this college, Pandit Hemraj was an esteemed educator and mathematician noted for his contributions to number theory and his leadership. He was also a member of the executive committee of the Indian Mathematical Society (IMS). At that time, university professors used to teach M.A. jointly at the three colleges in Lahore.

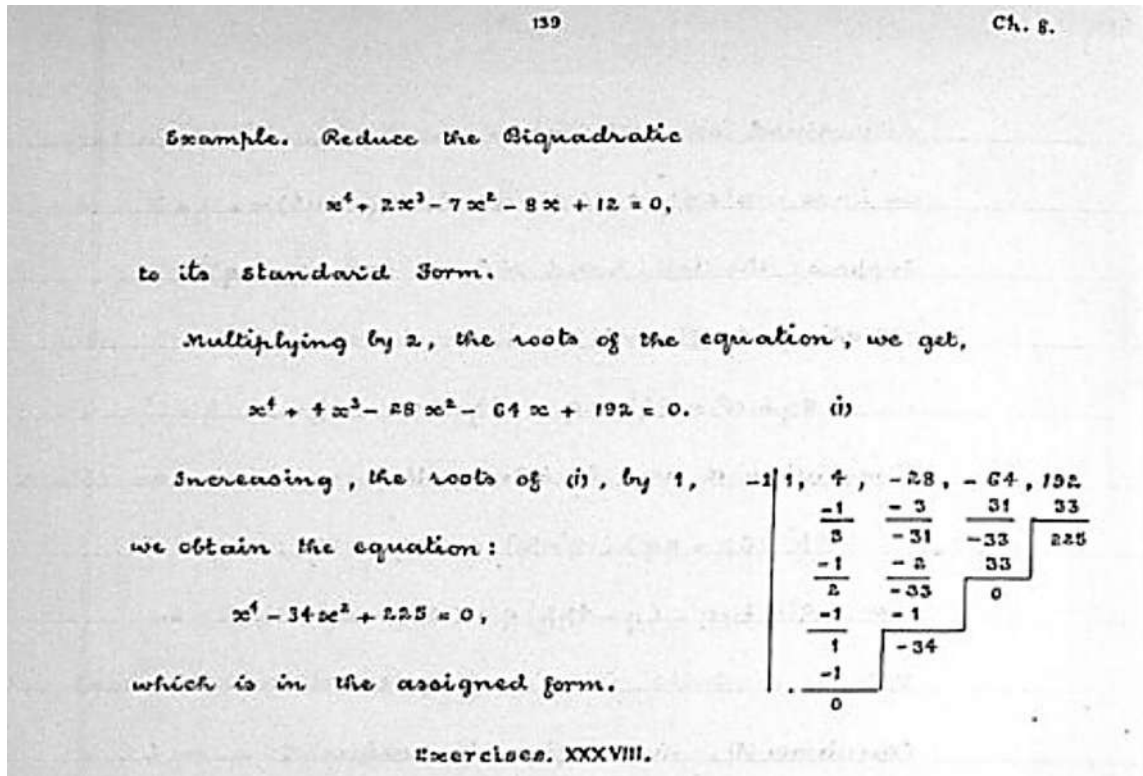
### 2.2 Later Career and Challenges

Because of limited academic facilities at Hoshiarpur, Hansraj regularly visited Lahore to consult books and scholarly journals in its libraries. Supported administratively by his Principal, Dr. Bihari Lal Bhatia (D.Sc., Zoology, Punjab University, 1932), he ultimately submitted his Ph.D. thesis to the University of Punjab, Lahore, in 1935. He was awarded the first Ph.D. in Mathematics in 1936 by PU in its over 50-years history. The thesis, entitled *Contribution to the Theory of Numbers*, was examined by J. E. Littlewood and G. H. Hardy, the two leading number theorists of the time. Hansraj Gupta's

handwriting was remarkably neat—almost resembling typescript—so he was given special permission to submit his thesis in handwritten form. Hansraj continued working at GCH until 1954.

Hansraj was promoted to the gazetted rank of the

Punjab Education Service, Class II, in 1945, and later to Class I in 1954. Following Partition, GCH came under the administration of Panjab University, and Hansraj was appointed Professor at the Department of Mathematics. In 1958, this department was relocated to Chandigarh.



A sample page from the notebook of Hansraj Gupta while he was at Dayal Singh College

At PU, his colleagues included Ram Prakash Bambah and Indar Singh Luthar. Under their leadership, the Mathematics Department at Panjab University, Chandigarh, made such rapid progress that the UGC granted it the status of a Centre for Advanced Study in Mathematics. After retiring in 1966, Hansraj continued his association with the Department of Mathematics as an Honorary Professor.

### 2.3 Passion for Partitions

For the greater part of his career, Hansraj Gupta served in small towns without adequate library

facilities or fellow mathematicians for academic discussion. As a result, he was largely unaware of contemporary developments and did not even know that the problem he had chosen to investigate was not entirely new. Nonetheless, he developed a deep passion for partition theory and its congruence properties, to which he made significant contributions throughout his life. His first publication on the subject had title *A Table of Partitions*. With the publication of extended versions of these tables by the Royal Society of London in 1958, Dr. Hansraj Gupta gained international recognition, and the tables later found

applications in disciplines such as computer science and statistical mechanics.

Hansraj Gupta recalled that sometime in 1929 or 1930, a student brought him a problem from an algebra textbook that stated, *“In how many ways can four mangoes be distributed among four persons when there is no restriction as to the number of mangoes any of them may receive?”* (see Chopra, 2024).

The student had previously approached another teacher, who assumed the mangoes to be all distinct and arrived at the answer  $4^4 = 256$ . As this did not agree with the answer provided in the book, the student approached Prof. Hansraj Gupta for an explanation. Professor Gupta assumed the mangoes to be indistinguishable and approached the problem accordingly. The answer agreed with the textbook, and the student was pleased that the problem had been resolved correctly. Yet, as Prof. Hansraj Gupta later noted:

*“Here the student’s problem ended, but mine had begun. I had noticed that what I had done was to partition 4 into at most four parts. I asked myself: ‘How many partitions will a given number have into a given number of parts?’ This is what I started investigating.”* (see Chopra, 2024).

Professor Hansraj Gupta was elected as President of the Indian Mathematical Society (IMS) in 1963. In December of that year, at the 29th Annual Conference of the IMS in Madras, he presented a presidential (technical) address on the topic “Partitions: A Survey,” where he reviewed various types of partitions and related problems. He worked in discrete mathematics and combinatorics, and made significant contributions to partition theory.

Professor Hansraj Gupta published around 70 research papers on partitions, solved numerous

conjectures, and posed many original problems. During an academic career spanning more than six decades, he published 190 research papers, six books and monographs, and collaborated with 16 mathematicians.

### 3. Ram Parkash Bambah: An Institution Builder



*Professor Ram Parkash Bambah*

Another legendary number theorist of the Panjab School of Mathematics was Professor Ram Prakash Bambah, a distinguished student of S. Chowla at GCL. He passed away earlier this year, on May 26, 2025, in the hundredth year of his life. To honour his remarkable contributions to mathematics, the Department of Mathematics had planned to organize an international conference as part of the centenary celebrations of Professor Bambah’s birth. We had all eagerly looked forward to celebrate his 100th birthday with him on September 30, 2025, but destiny had other plans. He left us merely four months before reaching that extraordinary milestone. While he is no longer with us in person, his spirit, scholarship, and vision continue to illuminate our paths.

Ram Parkash’s father, Bhagat Ram Bambah, was a Railway Guard who later rose to become a Chief Yard Master. His mother, Lajwati, had no formal education but possessed a sharp mind for mental calculation, having learned to calculate and write Punjabi at a Gurdwara school. Ram Parkash

Bambah was the sixth child in the family, with only two surviving elder sisters.

In 1954, while returning from England by ship, Bambah met Saudamini Parija who was also returning India after becoming a Fellow of the Royal Colleges of Physicians at U.K. She was the daughter of Prana Krushna Parija, a Padma Bhushan awardee and former Vice-Chancellor of Utkal University. They got married on 23rd February 1956 and were blessed with a daughter in a year, Bindu Bambah who grew up to be a famous physicist with a doctorate from University of Chicago. Bindu has a younger sister Sucharu Bambah.

The Bambahs were known for their warm hospitality on Panjab University campus. Saudamini was quite active in the social life of the campus and of Chandigarh at large. She served as member of the PGI Ethics Committee at PGI Chandigarh and President of the Chandigarh Chapter of the Indian Society of Blood Transfusion. She was also one of the founders of Ankur School on the PU campus. Saudamini passed away on 14th November 2011 after a brief illness (see Aravinda et al. 2020 and Hans-Gill et al. 2015).

### 3.1 From Lahore to Cambridge

In 1946, after his M.A. and a brief stint in undergraduate teaching, Chowla enabled R. P. Bambah to obtain a research scholarship at GCL. Chowla introduced Bambah to the  $\tau$ -function of Ramanujan, and the latter proved several results for this function. During 1936–1940, Hardy presented a series of lectures on the work of Ramanujan, the 10<sup>th</sup> lecture of which was on the  $\tau$  function. Bambah was highly inspired by these talks and published a series of 10 research papers along with S. Chowla, D. B. Lahiri, and Hansraj

Gupta on this function. The  $\tau$ -function holds a central place in modern mathematics due to its deep connections with elliptic curves, modular forms, and other key concepts, that were instrumental in proving Fermat’s Last Theorem.

In late 1945, while awaiting his official M.A. results, a serendipitous opportunity arose. Professor Chowla recommended him to Hansraj Gupta at Government College, Hoshiarpur, to fill in for a faculty member on leave. Bambah went merely to “see the place,” but Gupta, a man of action and generosity, took him to meet the Principal. “You start teaching tomorrow,” the Principal declared. Unprepared, with few belongings and no place to stay, Bambah was hesitant. But Gupta, with a kindness that would define their lifelong friendship, offered him a bed in his own home and even lent him shirts. This three-month period in Hoshiarpur solidified a deep bond between Bambah and the Gupta family (see Aravinda et al. 2020 or p. 66-67 Mukherjee, 2020).

In February 1947, Bambah joined Delhi University at the invitation of D. S. Kothari, taking up the Research Fellowship earlier held by F. C. Auluck. This fellowship was supported by the National Institute of Science of India, presently known as the Indian National Science Academy (see Aravinda et al. 2020). He was strongly supported by both Kothari and Auluck. Acting on their advice, he applied for the ‘1851 Exhibition Scholarship’ and subsequently earned his Ph.D. in 1950 from the University of Cambridge, working under the eminent number theorist L. J. Mordell.

Around this period, H. Minkowski developed geometric approaches for proving inequalities related to numbers, which eventually evolved into the thrust area of number theory, now known as the ‘Geometry of Numbers’. Bambah worked in this vibrant environment, surrounded by eminent

number theorists working in the ‘golden age’ of this area. In 1951, he produced four research papers from his thesis, further developing results previously published by Mordell.

During the final year of his ‘1851 Exhibition Scholarship’, Bambah spent some time at University College, London. In 1950–51, he co-authored three papers with C. A. Rogers, H. Davenport, and K. F. Roth, the latter being a future Fields Medallist (1958). Between 1952 and 1955, he was an elected Fellow of St John’s College, Cambridge, an honour earlier conferred on Abdus Salam, a student of Chowla. In 1951, Bambah returned to India and rejoined his earlier post at Delhi University, and in 1952 he was appointed Reader at Panjab University, Hoshiarpur (Mukherjee, 2020, pp. 66–67).

### 3.2 Establishing a Centre for Mathematical Excellence

In 1952, at the time of his appointment as Reader at Panjab University (PU), Hoshiarpur, Bambah received an offer of membership at the Institute for Advanced Study, Princeton. The then Vice-Chancellor of PU sanctioned special leave, allowing him to spend two years in the U.S.A. He returned in 1954 to continue teaching at Hoshiarpur with Dr. Hansraj Gupta, teaching M.A. classes.

After a stint of another year at Notre Dame University (1957–1958) on leave of absence, Dr. Bambah returned to contribute to the development of a vibrant Department of Mathematics at Panjab University, Chandigarh, along with Hansraj Gupta. Their efforts were supported by successive Vice-Chancellors and strengthened by new initiatives under the UGC. Bambah’s academic partnership with Hansraj Gupta was remarkable, especially in an academic environment often

marked by strong individualism. Their collaboration ensured the continuation of the Punjab School of Mathematics in post-independence India. Bambah was subsequently promoted to Professor. With faculty members such as Bambah, Luthar, and Gupta, the Department of Mathematics at Chandigarh attained UGC Centre for Advanced Study (CAS) status as early as 1963. In 1983, when the Government of India established the National Board for Higher Mathematics, this centre was selected as its first regional hub.

### 3.3 Research Contributions

Bambah made notable contributions to number theory, geometry of numbers, theory of coverings, in determining thinnest lattice coverings, densities of spheres, advancing work begun by Dirichlet in 1842 and inspiring further developments in the field. Professor Bambah, along with his students Vishwa Chander Dumir and Rajinder Jeet Hans-Gill, contributed notably to non-homogeneous quadratic forms, covering problems and Minkowski’s conjecture.

In 1899, the conjecture was proved by Minkowski for  $n=2$ . By the early 1970s, proofs had been given by various mathematicians for  $n=3, 4$  and  $5$ , but these proofs were complicated, and for  $n=5$  the proof was not quite rigorous. Bambah, together with A. C. Woods, provided proofs in these cases which were simpler and rigorous. He continued to work on related problems and promoted studies on the conjecture. Later, Professors R. J. Hans-Gill, Madhu Raka, and Dr. Leetika of the Punjab School of Mathematics extended this work for  $n = 7, 8$  and  $9$ .

Bambah authored around 70 research papers during 1946 to 2000. He was designated as Emeritus Professor of Mathematics at Panjab

University in 1993, two years after he relinquished Vice Chancellorship (1984-91) at PU. He received a Sc D degree (Doctor of Science) from Cambridge University in 1970 (see Hans-Gill, 2013). He was also awarded D.Sc. (*Honoris Causa*) by PU for his outstanding contributions in 2016. Professor Bambah held elected Fellowships of all three major Indian science academies—the Indian National Science Academy, the Indian Academy of Sciences, and the National Academy of Sciences—and was additionally a Fellow of The World Academy of Sciences (TWAS).

### 3.4 A Rich Mathematical Tapestry: Notable Women and Others at PU

Apart from the above three stalwarts, the Punjab School has produced several other notable mathematicians. Among them, Professor Indar Singh Luthar stands out for his contributions to diverse branches of number theory. His four Ph.D. students—Jagdish Chander Parnami, Sudesh Kaur Khanduja, Ashwani Kumar Bhandari, and Poonam Trama—served as faculty members in this department until their superannuation. A prolific writer, Professor Luthar, together with another stalwart of this department, Professor Inder Bir Singh Passi, authored a remarkable four-volume series of textbooks on Groups, Rings, Modules, and Fields.

Professor A. R. Rajwade, another prominent number theorist of the Punjab School, made significant contributions to Algebraic Number Theory, particularly in three areas: cyclotomy and roots of unity, arithmetic on elliptic curves with complex multiplication, and products and sums of squares in rings and fields. His collaborators included Dr. M. K. Agarwal, Dr. J. C. Parnami, and several of his students. Notably, he verified the Swinnerton-Dyer conjecture for elliptic curves. Professor S. A. Katre, a student of Professor

Rajwade, advanced work in cyclotomy by resolving ambiguities in cyclotomic numbers and Jacobi sums.

Among India's distinguished number theorists is Professor Rajinder Jeet Hans-Gill, who completed her B.A. (Hons.) and M.A. (Hons.) from Government College, Ludhiana, and later joined the Department of Mathematics at Panjab University for her Ph.D., where she worked under the supervision of Professor Bambah. In 1962, Bambah left for Ohio State University for a period of about two years, and fellowships were arranged there for his research scholars as well. Accordingly, Hans-Gill and Dumir moved to the United States and earned their Ph.D. degrees from Ohio State University in 1965 under Bambah's supervision. Their research contributions covered number theory and the geometry of numbers, particularly in maximal and minimal packing and covering problems, non-homogeneous quadratic forms, and work related to a conjecture of Watson. Professor Hans-Gill was awarded the D.Sc. (*Honoris Causa*) by Panjab University in 2025.

Another leading woman number theorist from the Punjab School is Professor Madhu Raka, who completed her Ph.D. under Professor Hans-Gill in 1979. She is widely recognized for contributions to the Geometry of Numbers and Algebraic Coding Theory. She is a Fellow of NASI and currently a NASI Senior Scientist (Platinum Jubilee Fellow) at Panjab University, she has helped resolve significant cases of classical conjectures—particularly those of Minkowski, Woods and Watson in higher dimensions.

Professor Sudesh Kaur Khanduja is another prominent woman number theorist from the Punjab School. She topped in PU in all years of her B.A. in Mathematics from Dev Samaj College for Girls, Ambala and completed her M.A. and Ph.D.

at Panjab University, Chandigarh, under the supervision of Professor I. S. Luthar in 1976. Her main research interests lie in Algebraic Number Theory, Function Field Theory, and Valuation Theory. She notably generalized the classical Schönemann–Eisenstein and Ehrenfeucht–Tverberg irreducibility criteria using Valuation Theory. Additionally, she extended certain theorems of Dedekind to valued fields. She has developed novel approaches to deal with classical problems in Algebraic Number Theory through the use of valuations, thereby enabling the potential extension of classical results to a broader class of rings.

Both Professor R. J. Hans-Gill and Professor S. K. Khanduja are Fellows of all three major science academies of India and of TWAS.

### **Enduring Legacy that Continues to Inspire**

To conclude, the coincidence of the hundred years of the Punjab School of Mathematics and the birth centenary of Professor R. P. Bambah marks a special moment for the mathematical community to reflect and celebrate. Beginning with the seminal contributions of Sarvadaman Chowla and distinguished figures such as Hansraj Gupta, and culminating in the far-reaching influence of Professor Bambah, the Punjab School of Mathematics developed a unique identity in number theory. Through pathbreaking research, engagement with leading global luminaries, and committed mentorship, they laid the foundations of a thriving mathematical culture in North India.

Four mathematicians of PU have received the coveted CSIR-Shanti Swarup Bhatnagar Prize in Mathematics, namely, Surinder Kumar Trehan (1931–2004) in 1976, Inder Bir Singh Passi (1939–2020) in 1983, Surender Kumar Malik (1942–2001) in 1985, and Tarlok Nath Shorey

(1945–) in 1987. Panjab University has produced five mathematicians who went on to serve as Presidents of the Indian Mathematical Society (IMS), namely, Hansraj Gupta (1963–64), R. P. Bambah (1969–70), I. B. S. Passi (2006–07), A. K. Aggarwal (2008–09), and Madhu Raka (2024–25).

### **Appendix**

The Department of Mathematics recently organized an International Conference on Algebra and Number Theory to commemorate the birth centenary of Professor R. P. Bambah. The event featured 12 distinguished speakers from India and abroad and attracted more than 120 participants (see Kainth, 2025). In this conference, Professor Sudesh Kaur Khanduja awarded three Best Paper Presentation Awards and proposed to donate more funds to ensure the continuation of these awards every year in celebration of Professor Bambah's birthday.

In 2015, Panjab University instituted the Annual Sarvadaman Chowla Memorial Lecture to commemorate the legacy of Professor Sarvadaman Chowla. The inaugural lecture, delivered by Fields Medallist Professor Manjul Bhargava to mark the 90th birth anniversary of Professor R. P. Bambah, set an inspiring precedent. This lecture series continues to encourage and shape young researchers in the discipline.

It is pertinent to add that the Mathematics Department block on the PU campus is named *Hans Raj Gupta Hall* and the *International Guest House of PU* is named after Sarvadaman Chowla. From September 30, 2025 onwards, the Auditorium of the Department of Mathematics has been named the *Professor R. P. Bambah Auditorium*.

**ACKNOWLEDGEMENTS:** The authors are indebted to Professor Sudesh Kaur Khanduja for

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**CENTURY OF THE PUNJAB SCHOOL OF MATHEMATICS**

# SCIENTIFIC INTERVENTIONS AND GREEN ENERGY FOR A SUSTAINABLE FUTURE AND RESILIENT EARTH

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## Abstract

The accelerating transition to green energy technologies is a critical pillar in addressing global climate challenges and fostering sustainable development. This chapter provides a comprehensive examination of state-of-the-art renewable energy advancements, including innovations in photovoltaic materials such as perovskite solar cells, wind turbine aerodynamic optimization, and emerging energy storage technologies such as lithium-ion and flow batteries. It highlights the integration of smart grid systems utilizing real-time analytics, artificial intelligence, and the Internet of Things to enhance energy management, grid resilience, and demand-side response. Furthermore, the chapter addresses carbon capture and storage techniques, hybrid renewable systems combining solar, wind, and bioenergy, and the role of emerging nuclear microreactors in decentralized energy generation. Challenges related to intermittency, system flexibility, lifecycle impacts, and economic scalability are analysed alongside policy frameworks, social acceptance, and global cooperation strategies necessary to advance a resilient and equitable low-carbon energy future. This synthesis highlights multidisciplinary approaches that encompass materials science, biotechnology, digital technologies, and regulatory innovation, collectively driving transformative progress toward net-zero emissions and sustainable planetary stewardship.

**Keywords:** Renewable energy innovations, photovoltaic technology, smart grids, carbon capture and storage, hybrid renewable systems, microreactors.

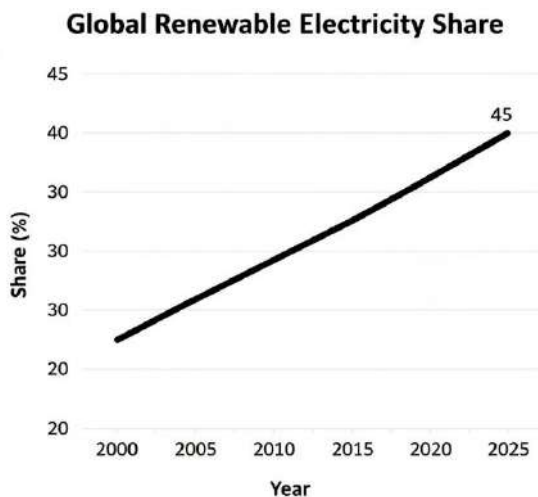
## 1. Introduction

In the 21st century, human progress must be balanced with environmental conservation. Unchecked industrial growth, urban expansion, and continued reliance on fossil fuels have intensified climate change, biodiversity loss, and pollution, threatening the planet's resilience. In this period of ecological crisis, moving toward sustainable and green energy systems has become not only a scientific necessity but also a moral obligation. Green energy includes solar, wind, hydro, geothermal, and bio-based systems that

provide cleaner, renewable alternatives to traditional fossil fuels [1]. These sources significantly cut greenhouse gas emissions and strain the planet's finite natural resources. Scientific innovation remains the driver of this shift. Advances in materials science have increased solar cell efficiency, reduced the weight of wind turbine parts, and extended the lifespan of energy storage solutions. Developments in biotechnology and nanotechnology have further improved biofuel production and carbon capture

methods, while digital technologies like Artificial Intelligence (AI) and the Internet of Things (IoT) have enabled more intelligent energy management and better grid performance [2].

Collectively, these growths are promoting a more integrated and intelligent energy ecosystem—one that highlights effectiveness, accessibility, and sustainability. However, realizing a truly sustainable and strong Earth demands more than technical growth alone [3]. It requires synchronized action across science, economics, governance, and society. Governments and industries must vigorously support green innovation through research funding, renewable energy incentives, and the implementation of environmentally feasible regulations. Equally essential is public participation and education, which cultivate awareness and encourage responsible energy consumption [4]. Through consistent technological progress with social, economic, and environmental relationships, humanity can shape a future in which growth and sustainability coexist. Such an approach ensures not only ecological conservation but also enduring stability and well-being for both people and the planet[5].



**Figure 1:** Global renewable electricity generation

## 2. Renewable Energy Technologies

Renewable energy technologies serve as the foundation of global efforts to attain sustainability (Figure 1) and ease the effects of climate change [6]. In contrast to traditional fossil fuels, renewable sources harness naturally replenished resources, viz., water, sunlight, wind, and biomass to generate clean and reliable energy. These technologies not only decrease greenhouse gas emissions but also improve energy security, generate new employment opportunities, and strengthen rural societies.

### 2.1. Solar Energy

Solar power remains among the most extensive and rapidly progressing renewable energy sources. It harnesses sunlight through photovoltaic (PV) cells or solar thermal systems to produce electricity. Cutting-edge revolutions, such as bifacial panels and perovskite-based solar cells, have meaningfully reduced production costs while increasing energy conversion efficacy [7]. From small-scale rooftop connections to extensive solar farms, these technologies are extremely scalable, having a pivotal role in encouraging dispersed and sustainable energy generation.

### 2.2. Wind Energy

Wind energy connects the kinetic power of moving air to produce electricity over wind turbines. Onshore and offshore wind farms are now the main contributors to global renewable capacity. Research continues to focus on lightweight turbine blades, advanced aerodynamic designs, and gearless systems that improve efficiency and reduce maintenance needs [8]. Offshore projects, in particular, profit from stronger and more reliable wind speeds, offering substantial potential for supportable energy production in coastal regions.

### 2.3. Hydropower

Hydropower produces electricity by combining the kinetic and potential energy of flowing or falling water. It remains one of the most established and efficient clean energy technologies [9]. While huge dams continue to play a key role in safeguarding grid stability and energy storage, small-scale and micro-hydro organizations are gaining importance in rural parts for decentralized power generation. Current research highlights low-impact designs, such as run-of-river systems, that minimize ecological disturbance and encourage sustainable water source management [10].

### 2.4. Biomass and Bioenergy

Bioenergy is derived from organic resources such as wood residues, algae, and agricultural waste. These materials can be transformed into useful forms of energy, viz., liquid biofuels like bioethanol and biodiesel, in addition to heat and electricity, through processes viz., anaerobic digestion, gasification, and fermentation. By recycling biological waste and reducing releases from landfills, bioenergy technologies help close the carbon loop and support a circular economy. Advances in enzymatic catalysis and genetic engineering are further enhancing biofuel efficiency and yield, visualizing biomass a vivacious component of sustainable energy systems [11].

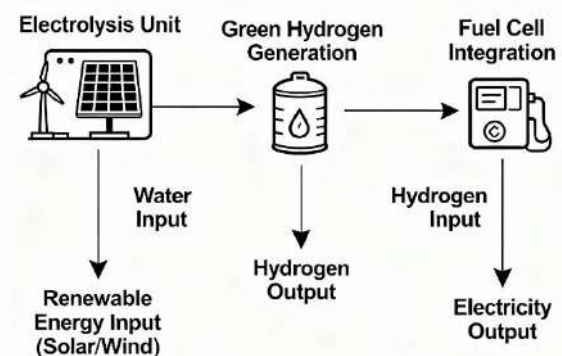
### 2.5. Geothermal Energy

Geothermal systems produce electricity or offer direct heating by applying the thermal energy stored underneath the Earth's surface. With a minimal release's geothermal plants offer a stable and nonstop source of renewable energy. Recent advances in examination techniques and enhanced geothermal systems (EGS) are increasing the

feasibility of this reserve beyond tectonic and volcanic zones, producing geothermal energy more broadly applicable in a wider range of topographical regions.

### 2.6. Emerging and Hybrid Systems

Hybrid renewable systems integrate multiple sources, viz, solar-wind or biomass-solar combination, to ensure a stable and uninterrupted power supply. The rise of green hydrogen, shaped through the electrolysis of water using renewable electricity, suggests a pathway for clean energy storage and transport. Hydrogen can power fuel cells, vehicles, and industrial processes, creating a bridge between renewable energy production and long-term energy security.



**Figure 2:** Hybrid Renewable hydrogen energy setup

## 3. Energy Storage, Grids, and Systems Integration

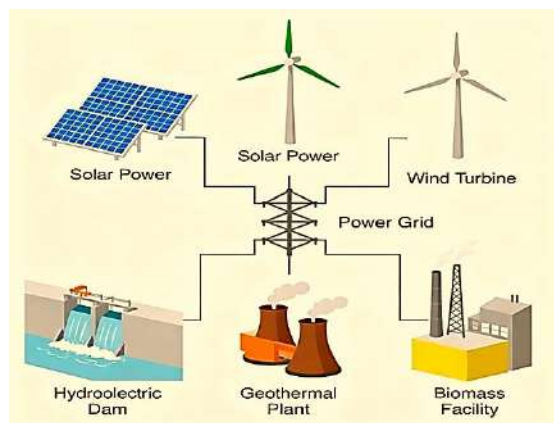
### 3.1 Grid Resilience & Fault Tolerance: Dealing with Intermittency, Extreme Events, and System Failures

The variety of renewable energy sources, viz., solar and wind, along with extreme weather events and emerging cyber-physical threats, grants increasing tasks to modern power systems. Fault tolerance as an essential aspect of resilience refers to the ability of a power network to maintain

continuous and dependable energy delivery in spite of disturbances or failures. Ongoing research discovers methods to enhance grid resilience via advanced monitoring, self-healing networks, predictive maintenance, and decentralized control, guaranteeing operational stability under dynamic and undefined conditions (figure 2).

### 3.1.1. Intermittency & Variability of Renewable Sources

- Renewables like solar and wind depend on weather, with their power output changing hourly and seasonally. The grid gets ahead with these changes to avoid disparity between generation and demand.
- Prediction plays a crucial role, where research shows that better meteorological models, combined with machine learning, allow more precise short-term predictions of solar irradiance or wind speed. This permits grid operators to acclimate schedules for dispatchable generators, adjust energy storage usage, and proactively adjust loads.
- Energy storage systems, viz., batteries, pumped hydro, thermal storage, are essential buffers. When generation surpasses demand, the excess is stored; through low renewable output, stored energy helps sustain supply.



**Figure 3** : storage of energy in power grids

### 3.1.2. Redundancy, Distributed Energy Resources (DERs), and Islanding

- Distributed Energy Resources (DERs) viz., rooftop solar, small wind, local battery storage, even local micro-generation, spread generation and storing across many points rather than directed in large central plants. This devolution reduces the risk of a single failure propagating across the whole system.
- Intended islanding is the planned disconnection of a part of the grid, often a microgrid or cluster of DERs + loads, from the main grid during faults or disturbances. This lets the islanded section to operate autonomously, by means of local generation and storage until normal operations can resume [12].
- Redundancy means having multiple pathways, alternative routes, and spare capacity viz., lines, transformers, and generation units, so that if one component fails, others can pick up the load. This is both in physical infrastructure, like multiple lines feeding a region, and in control/communication systems with backup sensors and alternate control channels [13].

### 3.1.3. Smart Grids, Microgrids, and Self-Healing Systems

- Smart grid technologies bring in digital monitoring, control, automation, and communication layers. They allow for real-time detection of faults or disturbances via sensors, phasor measurement units, advanced metering infrastructure, and rapid response [14].
- Microgrids play a critical role: they can function connected to the main grid in normal

times, providing flexibility, and then isolate themselves during faults or disasters. Because they are smaller and locally managed, they can often restore service more quickly. These are sometimes called self-healing grids when combined with reconfiguration capabilities and automated controls [15].

#### **3.1.4. Handling Extreme Weather & Large Disturbances**

Extreme weather (storms, heatwaves, floods) both increases the likelihood of component damage and of unusual load patterns (figure 3). A resilient grid should have a robust design for (i) infrastructure to withstand physical stresses like stronger poles, undergrounding lines in vulnerable areas. (ii) Flexible operational strategies to redirect power, shed or shift loads, or rely on energy storing when parts of the grid are disconnected. (iii) Resilient communication & control systems that can still function when parts of the infrastructure are disabled, like backup communication channels, decentralised control [16].

#### **3.1.5. Fault Detection, Isolation, and Rapid Restoration**

Sensors that are spread throughout the grid give visibility for faults. Once a fault is observed, automated detection methods allow for quick isolation to prevent damage and to limit the impact. The rapid restoration involves redirecting power through alternative pathways or using stored energy to supply critical loads until full repair [17].

### **4. Materials Science and Green Innovation**

#### **4.1. Eco-materials: Renewable, Biodegradable, and Low-Energy**

Materials science plays an essential role in

shaping a sustainable future by enabling the advance of eco-friendly materials that reduce ecological impact through their life cycle. Eco-materials are typically renewable, biodegradable, and characterized by low embodied energy, meaning that they require minimal energy during extraction, processing, and manufacturing. These materials, derived from natural and recyclable sources, are designed to seamlessly participate in ecological cycles without leaving determined waste [18].

Bio-based materials viz., bamboo, hemp, cork, and plant fibres, are increasingly being used in packaging, construction, and textiles due to their renewability and carbon-negative potential. They act as efficient acoustic and thermal insulators while reducing dependence on non-renewable resources like cement, plastics, and metals. The emphasis on low embodied energy has encouraged industries to substitute energy-intensive materials with those that are locally sourced, less processed, and recyclable, thus reducing overall carbon emissions [19].

#### **4.2. Nanomaterials, Bio-nanotechnology, and Biomimetic Materials**

The integration of nanotechnology and biotechnology has enhanced green innovation by creating materials that imitate natural structures or exploit nanoscale properties for enhanced performance. Nanomaterials viz., carbon nanotubes, metal oxides, and quantum dots, have transformed applications in solar energy, catalysis, and environmental remediation by improving efficiency, durability, and selectivity [20].

Biomimetic materials draw inspiration from nature's designs, viz., the self-cleaning ability of lotus leaves, the strength of spider silk, and the

light absorption of butterfly wings to develop advanced surfaces and composites. These materials are being integrated into sensors, solar panels, and catalytic systems to enhance performance while maintaining environmental compatibility. Bio-nanotechnology also enables the creation of recyclable nanocomposites and green catalysts that substitute toxic metals with naturally abundant elements, further reducing the ecological footprint of industrial processes [21].

#### **4.3. Life-Cycle Assessment: Manufacturing, Disposal, and Recycling**

A sustainable material's environmental impact spreads beyond its manufacture to its entire life cycle, from source extraction to disposal. Life-Cycle Assessment (LCA) provides a systematic approach to evaluate the energy use, emissions, and waste generated throughout each stage of a product's life cycle. It highlights the importance of considering not only the origin of materials but also their processing, transportation, usage, and end-of-life management [22].

Integrating LCA into material design motivates manufacturers to improve production processes, minimize waste, and select low-impact raw materials. Recycling and reusability are vital to this approach, ensuring that materials recollect their value within a circular economy. In clean energy technologies, for example, LCA helps assess the sustainability of solar panels, wind turbines, and batteries by identifying stages with the highest energy consumption or carbon output. Designing materials that are laid-back to disassemble, biodegrade, or recycle safeguards that innovation remains aligned with long-term environmental goals [23].

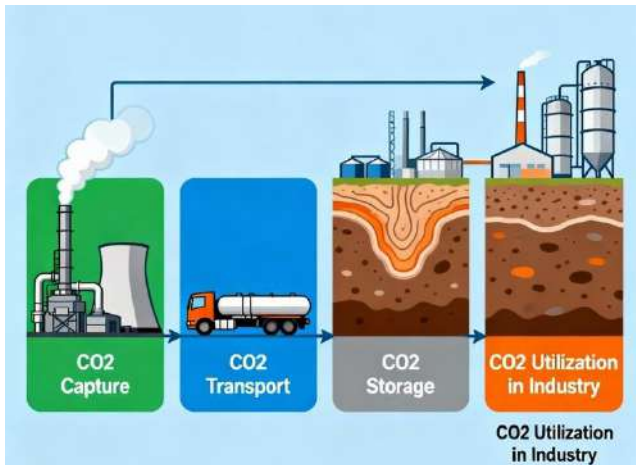
## **5. Carbon Management and Negative Emissions Technologies**

### **5.1. Carbon Capture, Utilization, and Storage (CCUS)**

Carbon Capture, Utilization, and Storage (CCUS) technologies are the most promising solutions for reducing greenhouse gas emissions from industrial and energy sectors. This process involves capturing carbon dioxide (CO<sub>2</sub>) from large emission sources, viz., power plants, cement factories, and steel industries, followed by either utilizing it in industrial processes or securely storing it underground.

Technically, CO<sub>2</sub> capture is through various methods, viz., chemical absorption, adsorption, cryogenic separation, or membrane-based filtration [24]. Once captured, the gas can be transported via pipelines and injected into geological formations like exhausted oil and gas reservoirs or saline aquifers, where it is trapped. Operational pathways include converting CO<sub>2</sub> into fuels, building materials, or chemicals, viz., methanol and urea, which add economic value while reducing atmospheric concentrations.

Economically, CCUS remains cost-effective due to high energy requirements and infrastructure demands. However, continued technological innovation and policy incentives are gradually improving its feasibility [25]. Safety is a major consideration, particularly in long-standing storage, where monitoring systems and strict regulations ensure that deposited CO<sub>2</sub> remains contained and does not contaminate groundwater or escape into the atmosphere.



**Figure 4:** carbon capture and utilization

### 5.2. Direct Air Capture, Bio-Sequestration, and Enhanced Weathering

Beyond point-source capture, Direct Air Capture (DAC) technologies extract CO<sub>2</sub> directly from ambient air using solid or liquid sorbents. Although DAC systems currently require significant energy input, advancements in renewable-powered operations are making them increasingly viable [26]. These systems offer flexibility as they can be deployed almost anywhere, helping offset emissions from sectors that are hard to decarbonize, such as aviation and agriculture (figure 4).

Bio-sequestration refers to the natural process of capturing carbon through biological systems — mainly forests, soils, and oceans. Practices such as afforestation, reforestation, and improved soil management enhance carbon uptake in biomass and organic matter. Similarly, enhanced weathering involves accelerating natural mineral reactions that absorb CO<sub>2</sub> from the atmosphere and convert it into stable carbonates. This technique holds promise for large-scale, long-term carbon removal, particularly when applied to agricultural lands or coastal zones. A combination of these approaches, biological, chemical, and

mechanical forms a comprehensive framework for negative emissions, balancing the carbon cycle and moving toward net-zero or even carbon-negative outcomes [27].

### 5.3. Carbon Markets, Incentives, and Ethics

The economic dimension of carbon management is governed largely by carbon markets and pricing mechanisms, which assign monetary value to CO<sub>2</sub> emissions and reductions. Through cap-and-trade systems or carbon credits, industries are encouraged to invest in cleaner technologies and carbon offsets (figure 5). These markets not only stimulate innovation but also create financial pathways for sustainable development projects, especially in developing countries [28].

However, effective carbon trading relies on transparent measurement, verification, and accountability to prevent misuse and ensure that emission reductions are genuine and permanent. Ethical considerations are equally significant. Relying excessively on negative emissions technologies without reducing fossil fuel use may foster complacency and delay essential transitions toward renewable energy. Therefore, carbon management should be viewed as a complementary strategy one that supports, but does not replace, deep decarbonization efforts [29].

A just and equitable carbon economy must ensure that vulnerable communities benefit from mitigation projects and are protected from adverse impacts such as land-use changes or displacement. Ultimately, integrating ethical governance with technological and economic innovation will define the success of global carbon management efforts.

## 6. Advanced Microreactors: A New Frontier in Clean Energy Generation

The growing demand for reliable, carbon-free, and adaptable energy sources has directed global attention toward advanced microreactor technology. Microreactors are compact, factory-fabricated nuclear power systems engineered to produce consistent energy outputs with exceptional safety and minimal environmental impact. Unlike traditional large-scale nuclear plants, microreactors operate at smaller capacities, typically ranging from 1 to 20 megawatts—making them suitable for decentralized and off-grid applications [30].

### 6.1 Design and Core Features

Microreactors are designed using modular and transportable architectures, allowing them to be assembled, transported, and installed quickly in remote or infrastructure-limited locations. Their sealed-core design minimizes the risk of radiation leakage and eliminates the need for frequent refuelling. Most models use high-assay, low-enriched uranium (HALEU) as fuel, which provides long operational lifetimes often several years before replacement is required [31].

Safety is the central feature of microreactor engineering. These reactors rely on passive safety mechanisms that use natural physical processes viz., convection, gravity, and thermal conductivity—instead of active mechanical systems. This ensures automatic cooling and shutdown during abnormal conditions, significantly reducing the likelihood of accidents or human error [32].

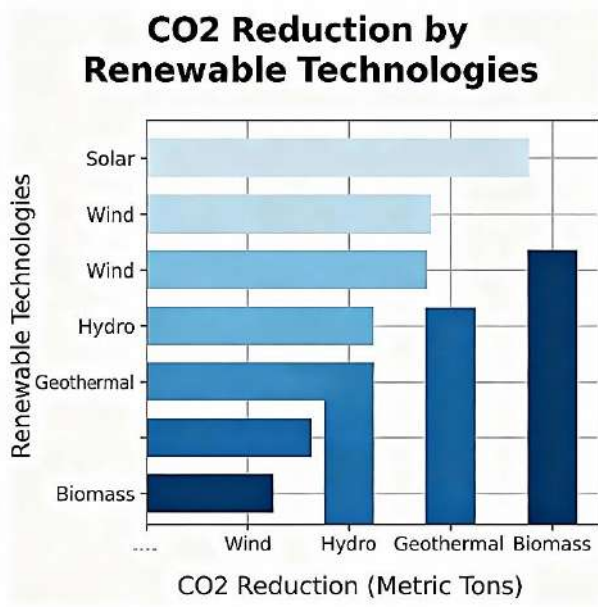
### 6.2 Operational Advantages

Microreactors offer several distinctive advantages over conventional nuclear and renewable systems:

1. **Scalability and Flexibility:** Their modularity allows integration with existing renewable infrastructures, such as solar or wind farms, to provide consistent baseload power and offset intermittency.
2. **Minimal Environmental Footprint:** Compact design and reduced fuel consumption translate into lower land use and less radioactive waste compared to large reactors.
3. **Rapid Deployment:** Since they are pre-fabricated in controlled industrial settings, microreactors can be deployed within months rather than the years required for traditional plants.
4. **Economic Viability:** Lower construction and maintenance costs make them suitable for developing regions or isolated grids where large power plants are economically unfeasible.
5. **Energy Security:** Microreactors can operate autonomously in remote or disaster-affected areas, providing critical power for hospitals, defence bases, or research facilities [33].

### 6.3. Integration with Renewable Systems

Microreactors are increasingly seen as a complementary technology to renewable energy systems. Their steady output can stabilize power grids that rely heavily on intermittent sources like solar and wind. When integrated into hybrid microgrids, they can support a continuous electricity supply while reducing carbon emissions, thereby creating a balanced and resilient energy ecosystem [34].



**Figure 5:** Carbon dioxide reduction by renewable Technologies

## 7. Policy, Economics, and Social Dimensions

### 7.1. Policy Instruments

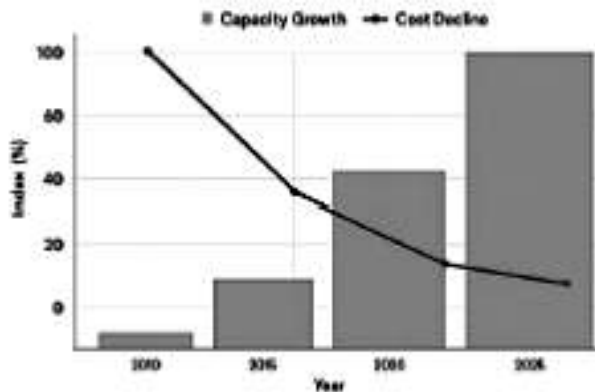
The successful adoption of green energy technologies depends heavily on robust and adaptive regulatory frameworks. Governments can implement subsidies, tax credits, and feed-in tariffs to encourage investment in renewable projects. Carbon pricing mechanisms, including carbon taxes and cap-and-trade systems, internalize the environmental costs of emissions, making low-carbon alternatives more economically viable. Regulatory measures such as renewable portfolio standards and mandates compel energy producers to meet minimum clean energy quotas, fostering long-term industry stability. Policies must also address infrastructure development, grid integration, and research incentives, ensuring that technological innovation is matched with market readiness [35].

### 7.2. Economic Viability

The transition to green energy is not purely technological it is also economic. Cost trajectories for clean energy technologies have been declining steadily due to improvements in efficiency, manufacturing scale, and supply chain optimization. Innovative financing models, including green bonds, public-private partnerships, and climate investment funds, are crucial in bridging the gap between pilot projects and large-scale deployment. The social cost of carbon, which measures the broader societal and environmental damages from emissions, reinforces the economic rationale for investing in clean energy. By quantifying these hidden costs, decision-makers can better justify renewable energy projects, even if initial capital expenditures are high [36].

### 7.3. Social Acceptance and Equity

Social factors influence the adoption of renewable energy. Public perception, community engagement, and transparent decision-making foster acceptance of renewable infrastructure. Equity considerations are equally vital; marginalized and vulnerable populations must benefit from energy transitions rather than bear disproportionate burdens. Expanding energy access in rural and underserved areas, creating green jobs, and implementing fair distribution of incentives are key elements of a just transition. Without social inclusion, even technically feasible and economically viable projects may face opposition or fail to achieve full impact [37].



**Figure 6:** Energy storage capacity growth and the cost decline

## 8. Challenges, Barriers, and Risks

### 8.1. Technical Barriers

Renewable energy technologies face technical challenges, with materials degradation, storage limitations, intermittent energy supply, and grid instability. Research in advanced materials, high-capacity batteries, and hybrid systems is critical to overcoming these hurdles.

### 8.2. Environmental Risks

Sustainable energy must also account for environmental trade-offs. Resource extraction for batteries and turbines, land-use changes for solar farms and biofuel crops, and biodiversity impacts are potential concerns. Mitigation strategies comprise circular material flows, project siting, and life-cycle environmental assessments [38].

### 8.3. Economic Constraints

High upfront capital costs, uncertain financial returns, and fluctuating energy prices can slow adoption. Stable policies, innovative financing, and risk-sharing mechanisms are essential to attract investment and ensure long-term viability (figure 6).

### 8.4. Social and Political Factors

Confrontation from communities, energy

inequity, and policy uncertainty are key social and political barriers. Engaging stakeholders early, ensuring fair distribution, and promoting transparency of benefits can overcome these obstacles and enhance project acceptance.

## 9. Roadmap and Future Directions

### 9.1. Research and Innovation

Future research should focus on high-performance materials, improved energy efficiency, longer durability, and scalable negative emissions technologies. Integrating disciplines such as materials science, biotechnology, nanotechnology, and AI can accelerate innovation [39].

### 9.2. Scale-Up Strategies

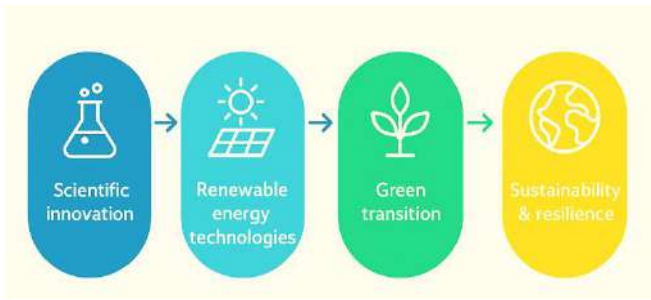
Translating laboratory successes to commercial-scale applications requires demonstration projects, replication in developing economies, and strong financing mechanisms. Public-private partnerships, international collaboration, and local capacity building are key enablers of scale-up.

### 9.3. Integration and Holistic Planning

Future energy systems must consider the interconnection between energy, food, and water systems. Holistic planning using economic principles, resource efficiency, and adaptive management ensures sustainability across sectors. Integrated approaches enhance resilience to climate shocks and optimize resource use [40].

### 9.4. Global Cooperation

International collaboration, climate finance, technology transfer, and coordinated policies amplify the impact of local initiatives. Shared innovation ecosystems, cross-border partnerships, and global knowledge networks are essential for meeting ambitious climate and sustainability goals.



**Figure 7:** Pathway to a sustainable and resilient earth

## 10. Conclusion

Scientific interventions and green energy technologies are central to creating a sustainable and resilient future. Innovations in materials, energy storage, energy conversion, and system integration, when combined with supportive policies, economic incentives, and active social engagement, can accelerate the global transition toward low-carbon energy systems. Every nation has a responsibility to protect the planet, reduce emissions, and embrace sustainable technologies. International conflicts and wars must be avoided, as peace is essential for coordinated environmental action. Technology transfer across borders should prioritize humanity and global well-being over economic gain, ensuring equitable access to sustainable solutions. Developed countries should formulate policies that assist underdeveloped nations in addressing pressing challenges such as poverty, food insecurity, health care, clean water, and education. Collaborative global efforts, guided by both innovation and ethical responsibility, are crucial to building a sustainable future. By fostering partnerships, sharing knowledge, and supporting inclusive development, nations can collectively reduce their carbon footprint, safeguard natural resources, and ensure a healthier, more resilient planet for future generations.

A multi-disciplinary approach, involving scientists, engineers, policymakers, and communities, is essential to ensure that these efforts are equitable, effective, and sustainable. Green energy extends beyond a technical approach but a cornerstone of resilience, environmental stewardship, and long-term prosperity, offering a vision of a planet powered by clean, efficient, and accessible energy for all.

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# THE ELECTRIC QUADRUPOLE INTERACTION OF $^{175}\text{RE}$ IN RE

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## Abstract

A high magnitude of EFG (electric field gradient) has been observed at  $^{175}\text{Re}$  in Re metal using the time differential angular distribution technique at room temperature. The magnitude of the axially-symmetric EFG in Re has been derived to be  $8.6(3) \times 10^{17}\text{V/cm}^2$ . These measurements point to the strong temperature dependence of the EFG in Re. The variation of the EFG with temperature is attributed to the localized d-electron in the non-cubic Re metal.

**Keywords:** Hyperfine interactions, Nuclear quadrupole moment, Electric field gradient, Time differential perturbed angular distribution.

## Introduction

The hyperfine-interaction studies have been crucial for both the condensed matter and the nuclear structure investigations. The hyperfine interaction energy is related to both the characteristics of a nuclear state, i.e., the magnetic moment and the quadrupole moment, and the electromagnetic fields at the nucleus due to the extra-nuclear electronic charge and spin distributions in the atoms or solids. Information about the one parameter can be extracted provided another one is known through some other investigations. Information about the one parameter can be extracted provided another one is known through some other measurements. Mostly the hyperfine interaction techniques, e.g., NMR/NQR, Mossbauer spectroscopy and the time differential perturbed angular correlation/distribution (TDPAC/D) techniques have been

employed for the nuclear structure and the condensed matter physics investigations (Butz,1996). The TDPAC/D techniques have the advantage over other techniques; a large number of probe nuclei are available across the periodic table for the hyperfine interaction studies and is not limited to the lower temperature also.

In most of the impurity-host combinations, the EFG measurements have been carried out through the Mossbauer and the NMR techniques, limited to the low temperatures, are not viable at room temperature. While the excited nuclear probe can be implanted into any host material, the impurity implantation creates the radiation damage in the host materials. The EFG due to the radiation damage is negligible as compared to that associated with the non-cubic crystal structure of the hexagonal closed packed (hcp) metals. In the

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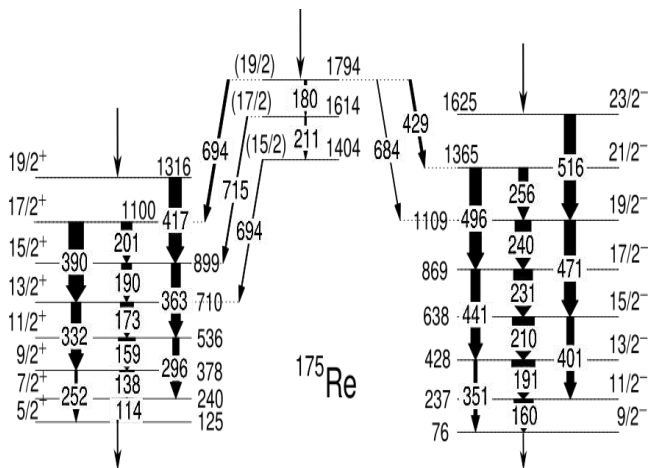
present investigations, we have carried out the electric quadrupole interaction measurements of the 3-quasiparticle  $I^\pi = (19/2)$  [ $E=1794$  keV,  $T_{1/2} \sim 27.7$  ns.] isomeric state in  $^{175}\text{Re}$  (Kibedi, 1992) recoil implanted into Re metal at room temperature and employing the TDPAD technique at Inter-University Accelerator Centre (IUAC), New Delhi. The bracket around 19/2 indicates the ambiguity in the spin-parity assignment of the state. Previously, Haas et al. (Haas, 1973) attempted electric quadrupole interaction measurements of  $^{187}\text{Re}$  (daughter product of  $^{187}\text{W}$ ), thermally diffused into Re single crystal, employing the differential angular correlation (DPAC) technique at room temperature. The quadrupole moment of the  $I = 9/2^-$  isomeric state in  $^{187}\text{Re}$  was derived by adopting the value of EFG at room temperature equal to that observed at 4.2 K, which is not true. Mostly the EFG in metals decreases with temperature (Christiansen, 1976 and Rasera, 1981).

### Experimental Details

The  $I^\pi = (19/2)$  isomeric state in  $^{175}\text{Re}$  was produced and aligned via the nuclear reaction  $^{165}\text{Ho}(^{16}\text{O}, 6n)^{175}\text{Re}$ , employing a 104 MeV pulsed  $^{16}\text{O}$  beam with a 250 ns repetition period delivered by the 15 UD Pelletron accelerator at the Inter-University Accelerator Centre (IUAC), New Delhi. The target consisted of isotopically enriched  $^{165}\text{Ho}$  with a thickness of approximately 700  $\mu\text{g}/\text{cm}^2$ , deposited on a 230  $\text{mg}/\text{cm}^2$  Re backing foil. The recoiling  $^{175}\text{Re}$  nuclei, emerging from the Ho layer in excited states, were implanted into the Re backing. Gamma rays emitted from the populated isomeric state were detected using two  $\text{LaBr}_3(\text{Ce})$  scintillation detectors ( $1\frac{1}{2}'' \times 1\frac{1}{2}''$ ), positioned at  $0^\circ$  and  $90^\circ$  w.r.t. the beam direction

in the horizontal plane, at a distance of 20 cm from the target.

The partial level schemes of  $^{175}\text{Re}$ , showing the decay of the presently investigated isomer, is shown in Fig. 1.

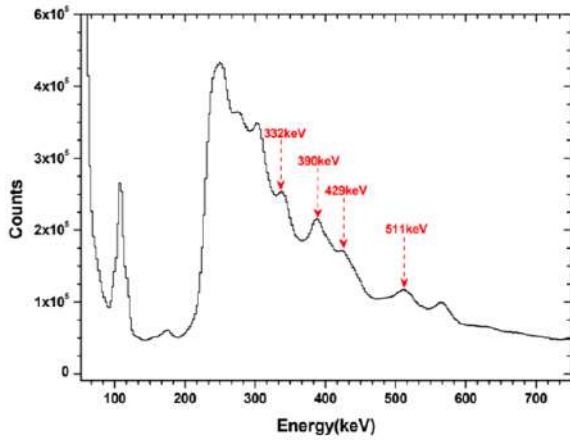


**Figure 1:** Partial level decay scheme of  $I^\pi = (19/2)$  isomeric state in  $^{175}\text{Re}$  (Kibedi, 1992).

### Data Analysis and Results

The data were acquired in list mode with four parameters - two energy signals and two timing signals obtained from the time-to-pulse-height converters corresponding to each  $\text{LaBr}_3(\text{Ce})$  detector. During offline processing, after proper gain matching for both energy and timing channels, two-dimensional energy-time matrices were generated for each detector. These matrices were subsequently employed to construct time-gated energy spectra and energy-gated time spectra for the system. A representative delayed  $\gamma$ -ray energy spectrum of  $^{175}\text{Re}$ , recorded using a  $\text{LaBr}_3(\text{Ce})$  detector, is shown in Fig. 2. The angular distribution of the emitted  $\gamma$ -rays exhibits perturbations caused by nuclear spin precession in the presence of the EFG (electric field gradient), superimposed on the exponential decay of the isomeric state. The time spectra from both

LaBr<sub>3</sub>(Ce) detectors were aligned by adjusting the time-zero ( $T_0$ ) reference, normalized, and background correction before being summed. The combined time spectrum was then examined using a least-squares (LSQ) fit to an exponential decay function to determine the half-life of the isomeric state. The resulting decay spectra for the (19/2) isomeric state in  $^{175}\text{Re}$  is shown in Fig.3.



**Figure 2:** Delayed  $\gamma$ -ray energy spectrum of  $^{175}\text{Re}$  without background subtraction.

In the presence of the EFG at Re nuclei in Re, the nuclear spin processes due to quadrupole interactions resulting into the time dependent modulation of the  $\gamma$ -ray intensity. The modulated time spectra at  $0^\circ$  &  $90^\circ$  were used to form the ratio factors  $G_{22}(t)$ ,

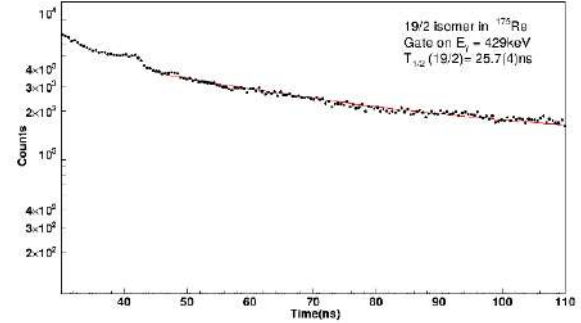
$$G_{22}(t) = \frac{2}{A_{22}} \frac{(I(0^\circ, t) - I(90^\circ, t))}{(I(0^\circ, t) + 2 * I(90^\circ, t))} \quad (1)$$

Here  $I( ; t)$  are the background subtracted and normalised time spectra at two angles  $0^\circ$  and  $90^\circ$ . The theoretical perturbation expression of  $G_{22}(t)$  for a polycrystalline sample and spins  $I = 19/2$  (Steffen, 1975) is,

$$G_{22}(t) = f \sum S_{2n} \cos(n\omega_{01}t)$$

$$\exp\left[-\frac{1}{2}(n \delta\omega_{01} t)^2\right] + (1 - f) \sum S_{2n} \cos(n\omega_{02}t) \exp\left[-\frac{1}{2}(n \delta\omega_{02} t)^2\right] \quad (2)$$

and has been used to extract the nuclear quadrupole interaction frequency  $\omega_{01}$ .

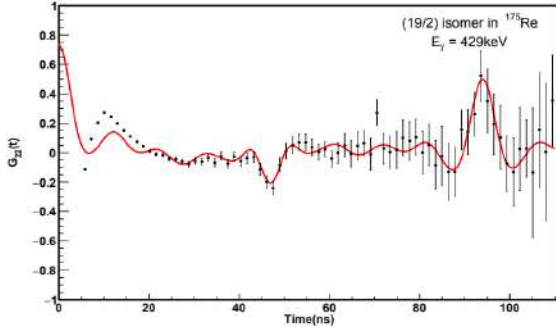


**Figure 3:** Life-time of the  $I^\pi = (19/2)$  isomeric state in  $^{175}\text{Re}$ . The solid curve shows the least squares fit to the data.

The experimental  $A_{22}G_{22}(t)$  function was analyzed using a least-squares (LSQ) fitting procedure incorporating two distinct components:

- (i) a fraction  $f$ , representing the self-implanted nuclei occupying regular lattice sites and experiencing a well-defined axially symmetric quadrupole interaction, and
- (ii) the remaining fraction  $(1-f)$ , corresponding to nuclei located at irregular sites and subjected to a broad distribution of quadrupole interactions.

For the  $^{175}\text{Re}$  nuclei, the fitted line in Fig.4. represents a LSQ fitted quadrupole interaction pattern for the  $I^\pi = (19/2)$  state with the interaction frequencies  $\omega_{01} = 66.9(2)$  Mrad/s and  $\omega_{02} = 15.1(9)$  Mrad/s corresponding to fraction  $f$  and  $(1-f)$ , respectively.



**Figure 4:** Spin rotation spectra of  $I^\pi = (19/2)$  isomeric state for the 429keV  $\gamma$ -ray transition in  $^{175}\text{Re}$ .

The fraction ( $f$ ) and the field distribution ( $\delta\omega_{01}$ ) at the regular sites are observed to be 75% and 0.012, respectively. The shape of the quadrupole precession patterns confirms the spin value,  $I = 19/2$ , of the isomeric state. The quadrupole interaction frequencies associated with the irregular sites are comparatively small and show little sensitivity to the distribution during LSQ fitting. For a half-integer spin state, the quadrupole interaction frequency  $\omega_{01}$  is related to the spectroscopic quadrupole moment ( $Q_s$ ) and the electric field gradient ( $V_{zz}$ ) through the following relation,

$$\omega_{01} = \frac{6eQ_sV_{zz}}{4I(2I-1)\hbar} \quad (3)$$

The quadrupole interaction constant ( $\nu_Q$ ),

$$\nu_Q = \frac{eQ_sV_{zz}}{h} \quad (4)$$

is independent of the spin of the state and depends only on the quadrupole interaction energy (product of the quadrupole moment and the EFG), and can be extracted from the above relation. The derived value of  $\nu_Q$  is 1213.7(4) MHz. The present measurements are not sensitive to the sign of the quadrupole interaction energy.

## Discussion

The observed value of  $\nu_Q$  corresponding to the 3-quasiparticle 19/2 state is comparatively higher than that of the single quasiparticle states,  $\sim 300\text{MHz}$ , in  $\text{ReRe}$  impurity–host system (Vianden, 1987). The magnitude of the efg can be extracted from the quadrupole interaction energy, provided the value of  $Q_s$  is known from some other measurements. At present the value of  $Q_s$  (19/2) is not known from the literature. The average of the calculated intrinsic quadrupole moment ( $Q_0$ ) values of  $I = K = 5/2$  and  $7/2$  states in Re nuclides,  $Q_0 = 7.92 \text{ eb}$  (Nazarewicz, 1990), may be adopted as the  $Q_0$  value of the 19/2 state. The equivalent  $Q_s$  value in the laboratory frame of reference can be derived under the strong coupling approximation,

$$Q_s = \frac{I(2I-1)}{(I+1)(2I+1)} Q_0 \quad (5)$$

It is an approximation, as there are experimental evidences of the shape co-existence in the  $A \sim 180$  mass region when the intruder  $h_{9/2}$  and  $i_{13/2}$  orbitals are occupied by the valence nucleons. The  $Q_0$  value is close to the value adopted by Kibedi et al. (Kibedi, 1992) for the intra-band analysis of  $^{175}\text{Re}$ . The extracted value of EFG is  $8.6(3) \times 10^{17} \text{ V/cm}^2$  at room temperature corresponding to the average value of  $Q_s$ . Which is much higher than that observed magnitude  $5.05(5) \times 10^{17} \text{ V/cm}^2$  at 4.2K (Rasera, 1981).

There may be the two reasons for this anomaly, either the real value of  $Q_s$  is large or the observed EFG at Re in Re has strong increasing tendency with temperature in variance to its reduction in sp-and transition- host metals (Christiansen, 1976 and Steffen, 1975). In the absence of any definite information about the configuration and the quadrupole moment of the (19/2) state, we can

adopt the average value of the quadrupole moment value for the isomeric state and look into the observed temperature dependence of the EFG in Re. There have been only two such type of investigations in Re host, i.e., ReRe (Stachel, 1983) and TaRe (Butz, 1975).

The EFG at Re in Re metal was observed to be enhanced  $\sim 1\%$  in the temperature range  $2\text{K} < T < 150\text{K}$  employing the Nuclear Acoustic Resonance technique (Stachel, 1983). It was not feasible to extend these measurements upto the room temperature. The only other EFG measurement corresponds to Ta impurity in Re metal in the temperature range 1.2K to 450K using the TDPAC technique (Butz, 1975). The temperature dependence of the EFG at Ta impurity in Re was observed similar to that of the Re in Re at low temperature, i.e., upto 150K. We can, therefore, assume the same temperature dependence for the ReRe system at higher temperature also. The enhancement of the EFG in TaRe was  $\sim 1\%$  in the observed temperature range. These observations points to the weak temperature dependence of the EFG at the transition metal impurities in Re metal, which is in variance to the assumed strong temperature of the EFG in ReRe metallic system. Therefore, a higher value of  $Q_S$  is expected in comparison to the assumed average value for the  $(19/2)$  state. The  $g$ -factor measurements in future can resolve this issue.

### Conclusion

The electric quadrupole interaction of the  $I^\pi = (19/2)$  isomeric state in  $^{175}\text{Re}$  has been investigated employing the TDPAD technique at IUAC, New Delhi. The high value of the quadrupole interaction energy  $v_Q$  points to the higher value of the quadrupole moment of the 3-quasiparticle  $(19/2)$

isomeric state as compared to that of the single-quasiparticle states. Further, the  $g$ -factor measurements are planned to determine the configuration of the state responsible for the high deformation of the state.

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# MAPPING PANJAB UNIVERSITY'S RESEARCH LANDSCAPE: A COMPREHENSIVE SCIENTOMETRIC ANALYSIS

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## Abstract

This study analyses Panjab University's research performance from 2020 to 2025, emphasising scholarly outputs, citations, collaboration patterns, and publication quality. It also looks at how research has had a bigger effect on society over this time. The SciVal platform was used to analyse data that had been taken out of Elsevier's Scopus database. International and academic-corporate cooperation contributions to the United Nations Sustainable Development Goals (SDGs), total publications, citations, Field-Weighted Citation Impact (FWCI), journal quartile distribution, and top-cited articles are some of the important metrics. With 11,326 articles written by 5,167 scholars over this time, 171,036 citations were generated, with an average of 15.1 citations per publication and an FWCI of 1.85. This indicates that Panjab University's (PU) research impact was far higher than the global average. International collaborations (27.4% of publications) had a disproportionately high impact (FWCI 3.96), whereas academic-corporate collaborations, which accounted for only 3.1% of output, had exceptional influence (FWCI 16.46, 104.5 citations per publication); nearly half of PU's publications (48.0%) appeared in Q1 journals, and 13.4% were among the top 10% most-cited globally. PU has thematic strengths in Physics, Materials Science, Engineering, Chemistry, Computer Science, and Biochemistry, with high-impact clusters such as Neutrino Mass and Higgs Mechanisms, Additive Manufacturing, and Deep Neural Networks. Panjab University helps society by writing 1,649 policy citations, 188 patents, and 4,160 media mentions. The research is directly linked to the core SDGs that deal with health, education, energy, and climate action. These findings demonstrate that Panjab University possesses robust interdisciplinary and influential research.

**Keywords:** Scientometrics, Panjab University, Research Impact, Collaboration, SciVal.

## 1. Introduction

In today's rapidly changing world of higher education, institutions are always competing for money, recognition, and resources. The major thing that helps them build their reputation is their research excellence. Because of this, institutions are using bibliometric and scientometric methods

increasingly to judge the quality and effect of their research. These methods made advantage of advanced analytics tools like Elsevier's SciVal and large citation databases. It lets institutions look at more than simply the amount of research effort; they can also look at the quality, influence,

collaborations, and impact on society. Panjab University (PU) is one of India's oldest and most well-known universities. It was founded in Chandigarh in 1882. PU has made contributions in many fields, but mainly in the physical and applied sciences. In today's digital world, nonetheless, a full review of PU's research performance is necessary. It needs measures that show how research affects the world. This study analyses PU's research performance from 2020 to 2025. We used the SciVal platform to look at data from Elsevier's Scopus database to find out PU's Field-Weighted Citation Impact (FWCI). It looks at trends in university research, partnerships, journal quality, and research clusters by topic. The study also looks at how PU's research affects people outside of academia. It found that PU work has a big effect on policy, patents, and news items that affect society. Also, PU's find the positives and work on the areas that need work. The total number of publications from Panjab University gives an overview by looking at the collaborations, journal standards, and main themes. It helps you understand more about the university's research profile. This rating helps put things in the bigger picture of worldwide research. It also helps to start important conversations about Indian universities and how they might improve their visibility, competitiveness, and overall importance in the academic community.

## 2. Review of Literature

The discipline of research assessment is well-established and uses a wide range of measurements, both quantitative and qualitative (Elsevier LibGuides, 2025). Bibliometric measurements provide a simple and dependable way to evaluate the output and impact of research. The citation indicators show how much research is available and how it affects others. The Field-Weighted

Citation Impact (FWCI) is a useful number that changes citation counts based on the year, kind of publication, and subject area. It makes guarantee that research in different domains may be compared fairly. The value 1.0 of FWCI is the average for the whole world. An FWCI of 1.85 means that the research gets 85% more citations than the average for the world. The FWCI allowed for the comparison of citation methods across different disciplines of study. It looked at the best ways to measure the impact of research. Some researches have shown that international collaboration gets more citations. This happens because it brings together people with various skills, resources, and a lot of visibility in research networks (Toney & Flagg, 2021; Wagner & Leydesdorff, 2005). In the same way, partnerships between institutions and businesses help people come up with new ideas that work in the real world. But figuring out and judging these associations frequently requires more detailed and complex methods (Perkmann et al., 2013; Cohen et al., 2023). Collaborations at the institutional level help get more work published and make it more prominent. This holds true whether institutions collaborate within extensive multi-institutional networks (Luo et al., 2014). The quality of journals is crucial for research evaluation because it is where research is published. According to Elsevier (2025), articles that are published in top-ranked journals (Q1) and journals with a high CiteScore frequently get greater attention and citations. Indicators such as policy citations, patents, and media attention are gaining significance in demonstrating real-world effect beyond the conventional academic sphere. They highlight its contributions to innovation, policymaking, and public understanding. Previous study on the Indian higher education system has identified both ongoing difficulties, such as inadequate

international linkages and underdeveloped translational research, and developing strengths in specific thematic areas (Gupta & Bala, 2011; Garg & Kumar, 2014). However, a thorough scientometric evaluation of Panjab University's (PU) recent performance, particularly using the entire set of indicators accessible in SciVal, remains unexplored. This study fills that vacuum by offering a detailed, evidence-based description of PU's research ecosystem, with a focus on the interactions between partnership kinds, thematic specializations, and social engagement.

### 3. Study Objectives

1. What are the trends and performance measures for Panjab University's research output from 2020-2025?
2. How does partnership type (international, national, institutional, or academic-corporate) affect research impact as evaluated by citation metrics and FWCI's?
3. Which subject areas and topic clusters highlight Panjab University's research strengths and growing fields during this period?
4. What are the societal benefits of Panjab University's research, including policy citations, patents, and media coverage?
5. How does Panjab University's research connect with and contribute to the United Nations Sustainable Development Goals?

### 4. Methodology

This study employs a quantitative, descriptive methodology utilising scientometric data. The SciVal analytics software pulled the dataset from Elsevier's Scopus database on June 25, 2025. The study looks at all the publications that Panjab University (PU) has published from 2020 until the

middle of 2025. The primary data sources for this research were the Institution Collaboration Report - Panjab University and the Institution High-Level Report - Panjab University. The two reports were made on July 3, 2025. The study utilised a comprehensive array of SciVal indicators, categorised into six dimensions:

#### 4.1 Productivity Metrics

- Scholarly Output: total number of publications.

#### 4.2 Impact Metrics

- Citation Count and Citations per Publication.
- Field-Weighted Citation Impact (FWCI).
- h5-index.
- Outputs in the Top 10% Citation Percentiles.

#### 4.3 Collaboration Metrics

- Geographical Collaboration: This comprises the percentage of output and FWCI for collaborations that happen between institutions, countries, or around the world.
- Academic–Corporate Collaboration: share of output and FWCI.
- Top Collaborating Institutions.

#### 4.4 Quality and Prestige Metrics

- Publications by Journal Quartile (based on CiteScore Percentile).
- Publications in Top Journal Percentiles.

#### 4.5 Thematic Analysis

- Distribution of publications by Subject Area (ASJC classification).
- Analysis of Topic Clusters and Key Topics based on scholarly output and prominence.

### 4.6 Societal Impact Metrics

- Number of Policy Documents that citing PU research.
- Number of Patents that cite PU publications.
- Mass Media Mentions.

The source reports were carefully used to get and organise the data. All of the tables and figures in the Results section were made using this data or made again. Chart.js was used to make visual charts that clearly display the important trends and comparisons.

**4.7 Limitation:** The research relies solely on data extracted from the SciVal database. The dataset was created using keywords and predefined filters for the analysis.

## 5. Results

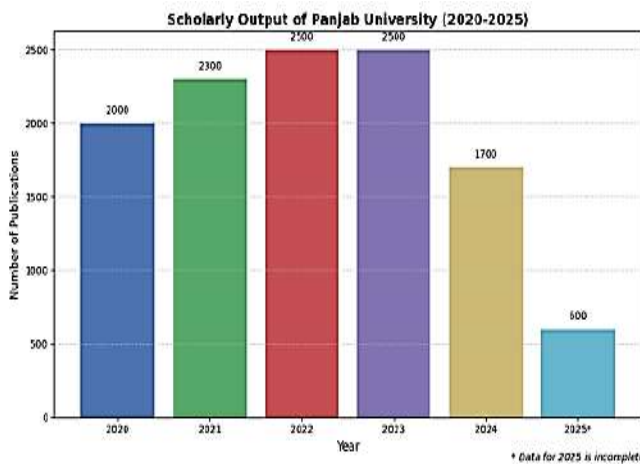
### 5.1 Overall Research Performance Metrics

Panjab University's (PU) strongly performed in research from 2020 to 2025 as shown in Table 1. During this time, the university published 11,326 papers by 5,167 researchers. These papers were cited 171,036 times, or an average of 15.1 times each. PU's Field-Weighted Citation Impact (FWCI) was 1.85. It signifies that the research was used 85% more than the average over the world. The h5-index of 108 also reveals that PU published a lot of important publications in the recent five years. Figure 1 shows the pattern of yearly publications. From 2020 to 2023, PU's research output expanded considerably, reaching almost 2,500 papers in 2023. In 2020, there were 2,000 articles; in 2021, there were 2,300; and in 2022 and 2023, there were 2,500 items. This revealed that research was going on a lot and in a constant way. In 2024, the number of publications fell to about 1,700. Changes in financing, delays in research, or

omissions in reporting may be to blame for this drop. There are just roughly 600 publications reported for 2025 thus far, so it's too early to compare this year to past years. The results in Table 1 and Figure 1 show that Panjab University is still doing a lot of research that has a big effect around the world.

**Table 1:** Summary Metrics for Panjab University (2020-2025)

| Metric                                | Value   |
|---------------------------------------|---------|
| Scholarly Output                      | 11,326  |
| Authors                               | 5,167   |
| Citation Count                        | 171,036 |
| Citations per Publication             | 15.1    |
| Field-Weighted Citation Impact (FWCI) | 1.85    |
| h5-index                              | 108     |



**Figure 1:** Scholarly Output by Year (2020-2025).

Note: The data for 2025 is incomplete.

### 5.2 Journal Prestige (CiteScore Quartiles)

The examination of Panjab University's (PU) academic output from 2020 to 2025 underscores

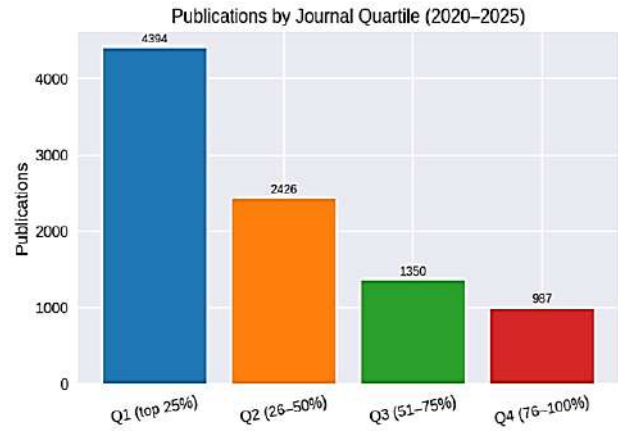
both the magnitude and calibre of its research activity. PU has certainly tried to get published in journals that have a big influence. Table 2 shows that nearly half of its publications (48.0%) were published in Q1 journals, while 26.5% were published in Q2 journals. This means that 74.5% of PU's research was published in the best journals in the world. The rest of the journals were in Q3 (14.7%) and Q4 (10.8%), which shows that they were published in more specialised or developing topics. The most articles are published in Q1 journals, followed by Q2, Q3, and Q4 journals. Figures 2 and 3 make this quite evident. Table 3 shows that 89.2% of PU's publications are in the top 75% of journals (Q1-Q3). These results show that PU is strong in both research output and impact.

**Table 2:** Share of Publications by Journal Quartile (2020-2025)

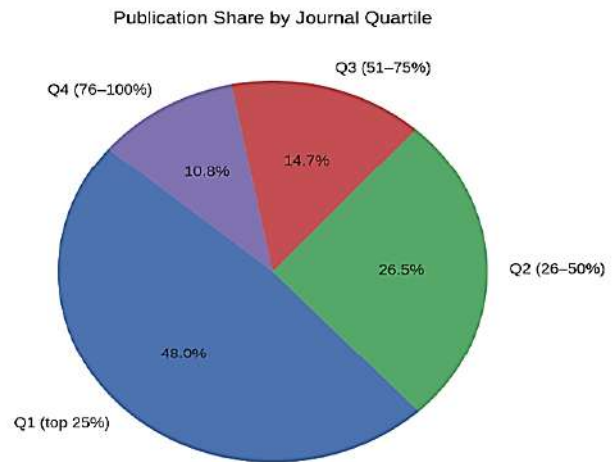
| Journal Quartile | Number of Publications | Publication Share (%) |
|------------------|------------------------|-----------------------|
| Q1 (Top 25%)     | 4,394                  | 48.0                  |
| Q2 (26%-50%)     | 2,426                  | 26.5                  |
| Q3 (51%-75%)     | 1,350                  | 14.7                  |
| Q4 (76%-100%)    | 987                    | 10.8                  |

**Table 3:** Cumulative Share of Publications by Quartile (2020–2025)

| Cumulative range   | Publications | Publication share (%) |
|--------------------|--------------|-----------------------|
| Q1 to Q2 (top 50%) | 6820         | 74.5                  |
| Q1 to Q3 (top 75%) | 8170         | 89.2                  |



**Figure 2.** Publication by journal quartile



**Figure 3:** Publication share by journal quartile

### 5.3 Collaboration structure and impact

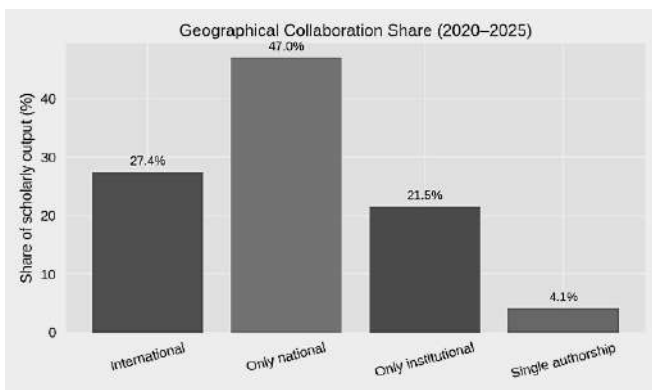
Panjab University's (PU) research output from 2020 to 2025 is heavily reliant on collaboration, which also significantly influences the institution's academic impact and visibility. Publication volume and citation performance vary significantly among collaboration forms, according to analysis of collaboration patterns (Table 4; Figures 4 and 5). International partnerships have a significantly greater citation impact even though they make up a comparatively smaller percentage of all articles. International co-

authored publications have a Field-Weighted Citation Impact (FWCI) that is much higher than the global average and receive substantially more citations per publication, demonstrating their increased prominence and impact. The bulk of PU's research output, on the other hand, comes from national and institutional collaborations, which only have a minor impact on citations and have FWCI values that are slightly higher than the global benchmark. Despite their small quantity, single-author articles have the lowest citation impact, suggesting a narrow scholarly audience. Academic-corporate partnerships exhibit a comparable discrepancy between volume and impact (Table 5; Figure 6). Despite making up a very small portion of PU's overall publications,

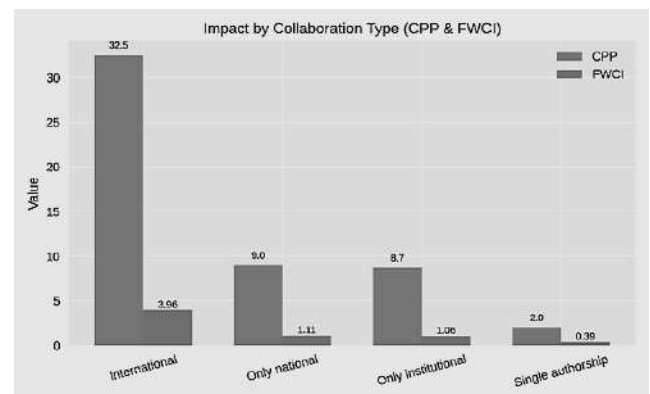
these partnerships provide remarkably high citation impact, with citations per paper and FWCI values far higher than those of non-corporate research. This result highlights the significant impact of industry-related research, indicating that even minimal interaction with corporate partners can produce very visible and influential academic results. Overall, the findings show that international and academic-corporate collaborations are the main forces behind Panjab University's strong citation impact and worldwide research awareness, while national and institutional collaborations maintain research productivity.

**Table 4 :** Impact of Geographical Collaboration (2020-2025)

| Collaboration Type                   | Scholarly Output (%) | Publications | Citations | Citations per publications | Field-Weighted Citation Impact (FWCI) |
|--------------------------------------|----------------------|--------------|-----------|----------------------------|---------------------------------------|
| International collaboration          | 27.4%                | 3,105        | 101,046   | 32.5                       | 3.96                                  |
| Only national collaboration          | 47.0%                | 5,321        | 47,882    | 9.0                        | 1.11                                  |
| Only institutional collaboration     | 21.5%                | 2,435        | 21,187    | 8.7                        | 1.06                                  |
| Single authorship (no collaboration) | 4.1%                 | 464          | 909       | 2.0                        | 0.39                                  |



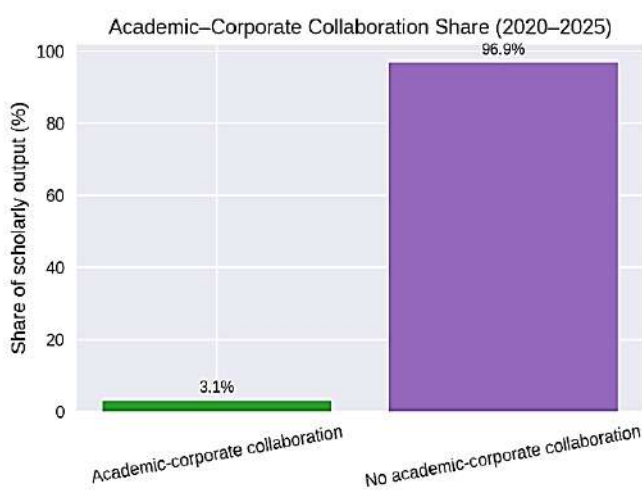
**Figure 4.** Geographical collaboration share (International, National, Institutional, Single authorship), 2020–2025



**Figure 5.** Impact by Collaboration type (CPP) and (FWCI)

**Table 5 :** Impact of Academic-Corporate Collaboration (2020-2025)

| Collaboration Type                  | Scholarly Output (%) | Publications | Citations | Citations per publications | Field-Weighted Citation Impact (FWCI) |
|-------------------------------------|----------------------|--------------|-----------|----------------------------|---------------------------------------|
| Academic-corporate collaboration    | 3.1%                 | 352          | 36,000    | 104.5                      | 16.46                                 |
| No academic-corporate collaboration | 96.9%                | 10,974       | 134,436   | 12.3                       | 1.38                                  |



**Figure 6.** Academic-corporate collaboration share

research effort seen in chemistry, life sciences, computer science, medicine, and environmental science in addition to these fundamental domains. Despite their relatively lesser bulk, the social sciences, pharmaceutical sciences, and mathematics are present, indicating a diverse research portfolio that goes beyond conventional laboratory-based fields. Overall, the distribution of subjects indicates that Panjab University aligns its research focus with industrial application, societal demands, and translational potential by striking a balance between basic scientific research and practical and socially relevant studies.

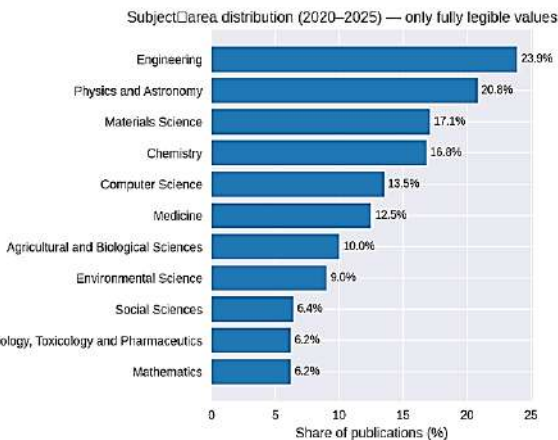
**5.4 Subject Areas Distributions and Research Specialisation**

The distribution of research output by subject from 2020 to 2025 at Panjab University shows a strong focus on fields driven by science and technology (Table 6; Figure 7). The top field is engineering, suggesting a strong focus on innovation and technical advancement. The university's ongoing strength in the physical sciences is demonstrated by the proximity of Physics, Astronomy, and Materials Science. A wide participation across interdisciplinary STEM subjects is demonstrated by the significant

**Table 6:** Subject Areas Distributions

| Subject Area                                 | Publication Share (%) |
|--|-----------------------|
| Engineering                                  | 23.9%                 |
| Physics and Astronomy                        | 20.8%                 |
| Materials Science                            | 17.1%                 |
| Chemistry                                    | 16.8%                 |
| Biochemistry, Genetics and Molecular Biology | 14.2%                 |
| Computer Science                             | 13.5%                 |

|   |       |
|---|-------|
| Medicine                                    | 12.5% |
| Agricultural and Biological Sciences        | 10.0% |
| Environmental Science                       | 9.0%  |
| Social Sciences                             | 6.4%  |
| Pharmacology, Toxicology, and Pharmaceutics | 6.2%  |
| Mathematics                                 | 6.2%  |



**Figure 7.** Subject area distribution (2020–2025).

### 5.5 Top Topic and Topic Clusters (by Scholarly Output)

Panjab University (PU) has excellent research strengths in many high-impact areas from 2020 to 2025 (see Table 7). The university is the best in basic physics, especially in Neutrino Mass and Higgs Mechanisms, with 500 articles (TC.27). It is also well-known in the fields of Quark Gluon Plasma and Phase Transitions, where it has published 324 publications (TC.175). These accomplishments demonstrate PU's enduring global influence in particle and nuclear physics. PU is also good at applied sciences. The university has made important contributions to

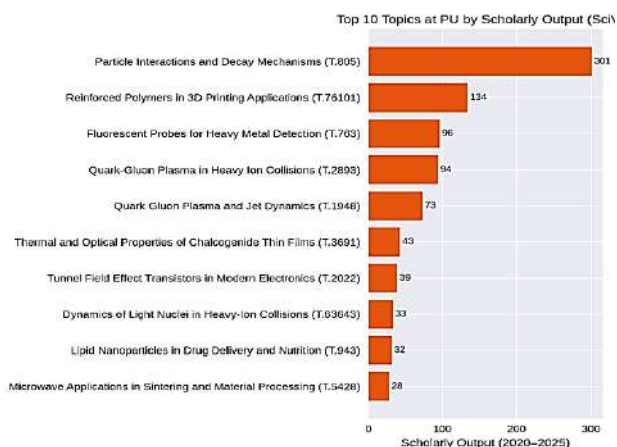
Additive Manufacturing and Material Properties, with 229 papers (TC.270). It is doing research on Two-Dimensional Materials and has published 102 publications (TC.92). The study of adsorption mechanisms for metal ion removal, which has 96 articles (TC.54), focusses on protecting the environment. Panjab University has featured a number of studies on COVID-19, its effects, and vaccination. These studies use fluorescence probes and molecular receptors to find and study the virus. It shows that PU has an impact in many fields and over the world. A high FWCI score is another sign of this. PU underlined the importance of undertaking research that helps individuals or has an effect on society.

**Table 7 :** Top 10 Topic Clusters by Scholarly Output (2020-2025)

| Topic Cluster   | Publications |
|---|--------------|
| <b>Neutrino Mass and Higgs Mechanisms (TC.27)</b>                           | 500          |
| <b>Quark Gluon Plasma and Phase Transitions (TC.175)</b>                    | 324          |
| <b>Additive Manufacturing and Material Properties (TC.270)</b>              | 229          |
| <b>Image Segmentation, Deep Neural Networks and Object Detection (TC.0)</b> | 190          |
| <b>Fluorescent Probes and Molecular Receptors in Detection (TC.562)</b>     | 169          |
| <b>COVID-19, Its Impact, and Vaccination (TC.1)</b>                         | 152          |
| <b>Nuclear Structure and</b>  | 126          |

|   |     |
|---|-----|
| <b>Dynamics in Astrophysics (TC.120)</b>                                |     |
| <b>Interactions in Particle Physics Models (TC.168)</b>                 | 102 |
| <b>Properties and Applications of Two-Dimensional Materials (TC.92)</b> | 102 |
| <b>Adsorption Mechanisms for Metal Ion Removal (TC.54)</b>              | 96  |

Figure 8 shows the most important subjects that PU studied from 2020 to 2025. "Particle Interactions and Decay Mechanisms (T.805)" has 301 outputs, and "Reinforced Polymers in 3D Printing Applications (T.76101)" has 134 outputs. It shows that individuals are interested in these areas.



**Figure 8 :** Top 10 Topics at PU by Scholarly Output (2020–2025)

Chemical detection is also significant, and "Fluorescent Probes for Heavy Metal Detection

(T.763)" has 96 papers on the subject. There are 94 papers on "Quark-Gluon Plasma in Heavy Ion Collisions (T.2893)" in nuclear physics. "Quark Gluon Plasma and Jet Dynamics (T.1948)" and "Thermal and Optical Properties of Chalcogenide Thin Films (T.3691)" are two other important topics. PU is also doing further research in electronics, biological uses, and material processing. Figure 8 demonstrates that PU has been working on particle physics, advanced materials, and new technology for more than five years.

**5.6 Top collaborating institutions (coauthored outputs)**

Panjab University's top ten research relationships include both big worldwide collaborations and strong ties with other institutions (see Table 8). The US Department of Energy is in the lead with 881 co-authored articles and a 2.34 FWCI, which shows how important PU is to big global physics projects. The Homi Bhabha National Institute (854 papers, FWCI 3.41), Wayne State University (848 publications, FWCI 6.27), and Italy's National Institute for Nuclear Physics (842 publications, FWCI 2.30) are also Close partners. Ohio State University (825 articles, FWCI 8.26) and CNRS France (795 publications, FWCI 5.41) are two important collaborators. PU also works with the National Institute of Science Education and Research (782 publications, FWCI 2.30), the Institut National de Physique Nucléaire et de Physique des Particules in France (766 publications, FWCI 2.34), and a few others, which are shown in table 8. These results suggest that Panjab University works well with other institutions. These partnerships help PU establish a big network that helps make research better all across the world.

**Table 8:** Collaborating institutions

| <b>Institution</b>   | <b>Co-authored publications</b> | <b>Citations (co-authored)</b> | <b>Co-authors</b> | <b>FWCI</b> |
|--|---------------------------------|--------------------------------|-------------------|-------------|
| <b>United States Department of Energy</b>                                    | 881                             | 20,242                         | 1,332             | 2.34        |
| <b>Homi Bhabha National Institute</b>  | 854                             | 19,735                         | 284               | 3.41        |
| <b>Wayne State University</b>  | 848                             | 44,479                         | 107               | 6.279       |
| <b>National Institute for Nuclear Physics</b>                                | 842                             | 18,394                         | 2,112             | 2.30        |
| <b>Ohio State University</b>   | 825                             | 57,822                         | 178               | 8.26        |
| <b>CNRS</b>  | 795                             | 22,028                         | 927               | 5.41        |
| <b>National Institute of Science Education and Research</b>                  | 782                             | 17,810                         | 118               | 2.30        |
| <b>Institut national de physique nucléaire et de physique des particules</b> | 766                             | 16,775                         | 763               | 2.34        |
| <b>Université ParisSaclay</b>  | 761                             | 27,454                         | 360               | 6.29        |
| <b>Fudan University</b>  | 740                             | 20,556                         | 87                | 6.57        |

### 5.7 Broader Impact: Policy, Patents, and Media

Panjab University has a big effect on policy, patents, and media coverage. The university's research isn't simply in the academic field; it has also been mentioned 4,160 times in the news. Additionally, 188 patents reference academic work, and 1,649 policy papers reference PU work. Table 9 and Figure 9 show how university research has distinct effects in these areas.

- **Policy Impact:** Panjab University has an impact on policy in the research field since 1,649 policy papers cited its research work. This data suggests that PU work somehow helps make policies. The university got 872 policy citations that assist them make choices concerning public policy.

**Technological and Economic impact:** The university's research has 188 patents, which shows that PU plays a significant role in

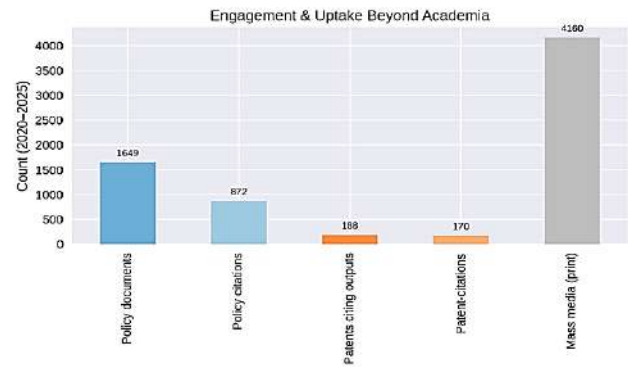
technology and industry. Additionally, 15 citations and 170 patent citations for every 1,000 papers show that PU's work influences the Knowledge landscape (see Figure 9).

- Societal Engagement and media visibility: During this time, Panjab University was mentioned in the news 4,160 times. It concludes that PU work was not only useful for academics, but also for those who were not involved in research.

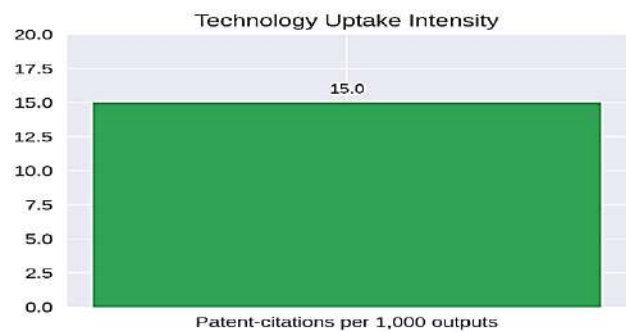
**Table 9:** Broader Impact: Policy, Patents, and Media

| Metric                             | Value |
|------------------------------------|-------|
| Field-Weighted Views Impact        | 2.35  |
| Policy Documents Citing PU         | 1,649 |
| Policy Citations                   | 872   |
| Patents Citing PU Research         | 188   |
| Patent Citations                   | 170   |
| Patent Citations per 1,000 Outputs | 15.0  |
| Mass Media Mentions (Print)        | 4,160 |

Figure 9 shows how PU is involved in different sectors. Policy texts and citations are important, but the major way people get involved in society is through print media. Patents and patent citations also indicate how technology is related. Figure 10 demonstrates that there are 15 patent citations for every 1,000 articles, which suggests that the technology has a big effect. These data show that PU has a bigger impact on policy, innovation, and society.



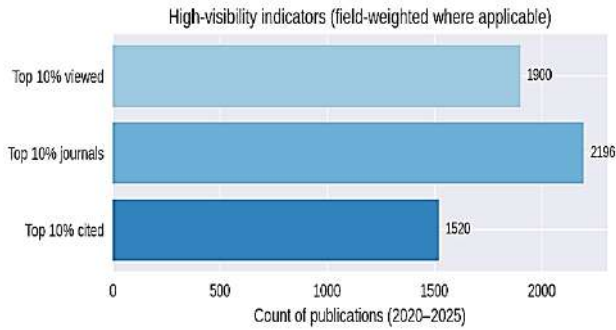
**Figure 9.** Policy and patent engagement, and mass media mentions (print)



**Figure 10.** Patent-citations per 1,000 outputs

### 5.8 High-visibility outputs

The examination of high-visibility metrics at Panjab University from 2020 to 2025 underscores its significant influence in academic publishing (Figure 11). The university produced 2,196 articles in the "Top 10% journals" during this time. This was the largest category and showed that the university was well-known in renowned, leading venues. 1,900 of PU's articles were in the "Top 10% viewed," which shows that they are very relevant to its research. At the same time, 1,520 papers were in the "Top 10% cited" category, which shows that they had a big impact on academics, but not as much as the number of journals and views. These field-weighted metrics show how well-known PU's research is and how many times it has been cited.



**Figure 11.** High-visibility indicators

**5.9 Most cited publications**

The papers from Panjab University have a big effect on citations in their fields. Table 10 shows

that "GBD 2019 - 369 diseases and injuries (Lancet, 2020)" has the most citations (12,435) and the greatest FWCI (518.69). This shows that research papers help people learn about how diseases spread over the world. The publication "GBD 2019 - 87 risk factors (Lancet, 2020)" has 6,265 citations, which is also a lot. It demonstrates the significance of understanding health risk factors. Table 10 further shows that PU is involved in research on stroke and diabetes and publishes findings on these topics. This PU study demonstrates the significance of such papers for global health research and policy. Also, PU work gets more citations in these areas that influence society.

**Table 10.** Most cited publications

| Publication (abbrev.)                                 | Citations            | FWCI   |
|---|----------------------|--------|
| GBD 2019 – 369 diseases and injuries (Lancet, 2020)   | 12435                | 518.69 |
| GBD – cardiovascular diseases (JACC, 2020)            | 7239                 | 141.01 |
| GBD 2019 – 87 risk factors (Lancet, 2020)             | 6265                 | 272.68 |
| GBD – Burden of stroke (Lancet Neurology, 2021)       | 3836                 | 281.72 |
| GBD 2021 – Diabetes prevalence to 2050 (Lancet, 2023) | 1971 climate action. | 504.27 |

**5.10 Sustainable Development Goals (SDG) Contributions**

Panjab University does a lot of research on the Sustainable Development Goals (SDGs), and most of their papers are on gender equality, good health, great education, and a clean environment (see Figure 12). PU has also published some papers on peace, justice, innovation, and climate action that are related to several SDGs. But PU is mostly interested in health sciences, medicine, and teaching. The results demonstrate that PU is also

beginning to publish work in the fields of sustainability, industry, and innovation. Now, Figure 13 also shows how the university affected other SDGs. The results indicate that the university actively engages in several SDGs, as seen by the data.

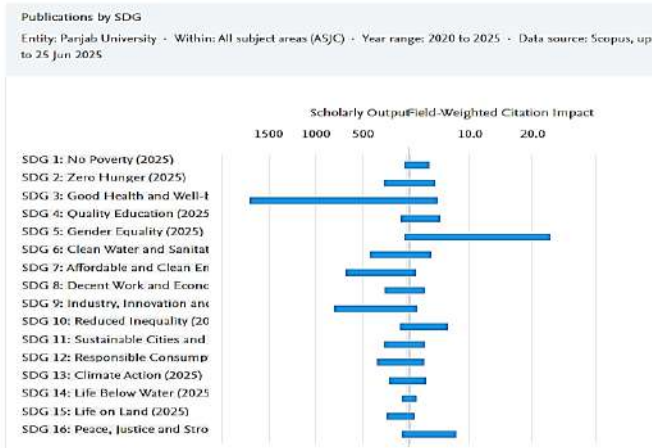


Figure 12. Publication by SDG

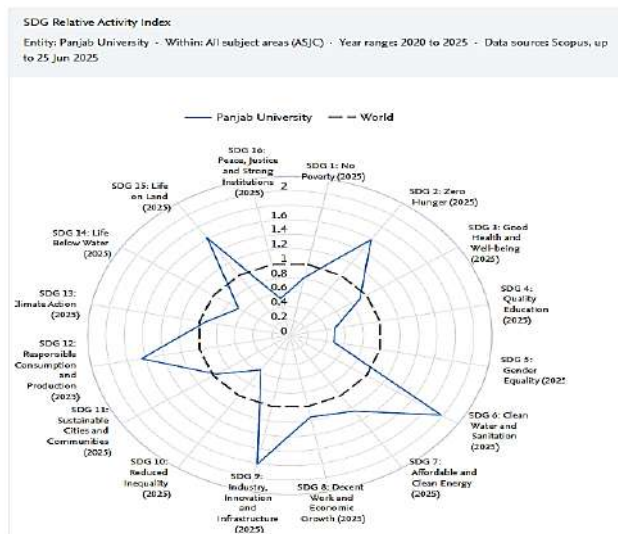


Figure 13. SDG Relative Activity Index

**Discussion**

The study of Panjab University (PU) from 2020 to 2025 shows that PU is an institution that focuses on research. It signifies that PU's study is getting more attention and has a bigger impact over the world. Also, PU's research is cited 85% more often than the average for the world. This means that the Field-Weighted Citation Impact (FWCI) is 1.85, which has a big effect on how visible research is. Publications in recognised journals and working

with high-impact collaborations are two things help PU to do so well.

**Interpreting Panjab University's High Impact**

The high FWCI of PU's publications shows that the university cares about the quality and impact of its research. As 48% of articles are in Q1 journals and 74.5% are in the top 50 journals (Q1-Q2), this is a good sign. The research papers in these periodicals make the work of PU more well-known to the public. Also, 13.4% of PU's outputs are in the top 10% of articles that have been cited the most around the world. It shows that the university has done good research.

**The Power of Collaboration: A Catalyst for Impact**

Collaboration is an important part of getting more research done. PU's articles are 27.4% from international collaborations. It has a high FWCI of 3.96 and obtains 32.5 citations for each piece of research it publishes. This has higher values than national (FWCI 1.11) and institutional cooperation (FWCI 1.06). It shows that PU has a lot of research connections around the world. The links between academics and businesses make up only 3.1% of university publications, but they have a much bigger effect. This means that PU's research works with fields like industry that affect both business and academic domains. It also shows that these kinds of partnerships help people learn more about things that affect society.

**Balancing Quantity with Quality**

PU's publications went from roughly 2,000 in 2020 to almost 2,500 in 2022-2023, which shows that the organisation is doing more research. The number of publications fell to 1,700 in 2024, while citation metrics and journal quality demonstrate that the quality of the research stayed strong.

Publishing in top journals and maintaining a high proportion of highly cited papers demonstrates a robust equilibrium of quantity and quality, which bolsters long-term reputation and ranking.

### Societal Relevance and Broader Impact

Panjab University has a big effect on society. Its research has had an impact on about 1,650 policy papers and resulted in 188 patents, which shows that it matters in the real world. PU is also quite well-known in the media, with 4,160 print mentions that assist spread awareness to the public. It indicates that PU research influences more than just the academic world; it also affects policy and innovation. PU also backs the SDGs, especially those that have to do with climate change, health, education, and new ideas. These donations make the university more powerful and help it get additional funding and partnerships.

### Conclusion

This Scientometric assessment of Panjab University from 2020 to 2025 concluded that the university's research publications had a big effect on society throughout time. One of the most important things to note is that PU's research has a much bigger influence than the norm around the world. The university is also very good at publishing in high-quality journals and has a lot of knowledge in the physical and applied sciences. The findings revealed that: (1) PU sustains a substantial research output, evidenced by a notable FWCI of 1.85; (2) its impact is significantly amplified through international or industrial collaboration, in contrast to domestic or institutional endeavours; and (3) the university's strengths are concentrated in high-impact domains of Physics, as indicated by Scopus-indexed publications. Scientometric metrics are helpful, but they do not show all about the quality of

research, the influence of education, or the worth to society. Additionally, future studies may use qualitative research to elucidate collaborative patterns. PU's clear plan to build on its capabilities while forming high-impact collaborations around the world. This method will help the university become one of the best places in the world for research.

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# MORPHOLOGICAL AND DNA BARCODING BASED IDENTIFICATION OF *FOUR SPECIES FROM* *GENUS DRACAENA VAND. EX L. (SANSEVIERIA THUNB.)*

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## Abstract:

DNA barcoding is emerging as a definitive tool for plant species identification, complementing traditional morphological approaches. It is particularly useful when species are difficult to distinguish during the vegetative phase or in forensic contexts where plant material is limited, degraded, crushed, or otherwise processed. The present study focused on the identification of four *Dracaena* species, earlier known as *Sansevieria*, using morphological characters as well as DNA barcoding based on the *rbcL* and *trnL* gene regions. As an exception, in this case, DNA barcoding did not clearly discriminate among the species, whereas morphological parameters were sufficiently distinct to reliably establish their identities.. However, submitting DNA barcode of these species in BOLD database will help in identification at least at genus level if the sample is morphologically unidentifiable due to degradation or crushing in a forensic case or medicinal preparation.

**Keywords:** Taxonomy, *Dracaena zeylanica*, *Dracaena cylindrica*, *Dracaena angolensis*, *Dracaena trifasciata*, *Dracaena kirkii*, *Sansevieria*, *rbcL*, *trnL*, DNA barcoding.

## Introduction

The genus name '*Sanseverinia* Thunb.', was originally given by an Italian Biologist 'Vincenzo Petagna' in the year 1787 to honor Italian nobleman 'Pietro Antonio Sanseverino'. The plant was growing in the garden of his patron. This angiospermic genus is a member of the family Asparagaceae and contains around 70 species. Recently, species of this genus have been placed in the genus '*Dracaena*' (Thu, 2021). Therefore, the species of genus *Sanseverinia* (*Sansevieria*) are nested with the genus *Dracaena* Vand. ex L. The genus *Dracaena* is a member of the family Asparagaceae, and it has about 179 species (Zhang, 2022). The genus name '*Dracaena*', refers to the Greek word 'Drakon' which means 'red

sap', produced by these plants, and it is similar to the Dragon's blood.

Species identification within the genera *Dracaena* and *Pleomele* remains problematic across different regions of the world. The phylogenetic analysis of selected species has mixed these two genera, while others stating them to be the distinct (Kleinwee, 2022). Based on different morphological features, the genus *Dracaena* has been placed in the family's including Liliaceae, Agavaceae, and Ruscaceae from time to time. These morphological based taxonomic problems are likely to be resolved by molecular studies. The molecular investigations coupled with the detailed statistical analysis can

help in the establishment of phylogenetic relationships (Lu, 1970).

The identification of plant species based on morphological characteristics has traditionally been a reliable approach; however, this method may fail to resolve the identities of closely related species. In recent years, DNA barcoding has emerged as a complementary technique for species identification to address this limitation (Stein, 2014). This molecular biology technique does not demand any detailed knowledge of morphology; a non-specialist can get it done just by determining the sequence of a specific region of its genome. This advantage has made it popular amongst researchers, specifically forensic scientist because sometimes the plant forensic sample is so minute or degraded that morphological identification is not possible. DNA barcoding is widely regarded as an efficient tool for distinguishing closely related species within a genus (Hebert, 2003). DNA barcode markers should be globally accepted and possess key characteristics, including universal primer sites that allow easy amplification across taxa, amplicons short enough for efficient sequencing, and sufficient sequence variability to enable reliable species-level identification (Chase, 2007). Numerous nuclear, mitochondrial, and plastid genomic regions—such as COI, *rbcL*, *matK*, ITS, *rpoC1*, *rpoB*, and *trnH-psbA*—have been successfully employed as DNA barcode loci. (Borovikova, 2017; Slugina, 2014; Sucher, 2012). Here, we have described a comparison of DNA barcoding and morphology based method for species identification amongst 4 species of genus *Dracaena*, that are, *Dracaena zeylanica*, *Dracaena cylindrica*, *Dracaena trifasciata*, and *Dracaena kirkii*. Genus *Dracaena* was earlier known as genus *Sansevieria*, therefore respectively they were *Sansevieria zeylanica*, *Sansevieria cylindrica*, *Sansevieria trifasciata*, and *Sansevieria kirkii*. *Dracaena cylindrica* is also known as *Dracaena*

*angolensis*. *Dracaena kirkii* is also known as *Dracaena pathera*. *Dracaena* is becoming a popular ornamental plant in India, therefore it can be a trace evidence in forensic studies. Species of this genus are known to be having ornamental, medicinal and aesthetic values as well as low maintenance requirement (Thu, 2021). In view of the importance of accurate species identification, this study presents a comparison of morphological and DNA barcoding-based approaches for identifying common species of the genus *Dracaena*. Plastid genomic regions *rbcL* and *matK* are most commonly used for plant DNA barcoding. In addition to these two genes, we also used the *trnL* region of the plastid genome.

### Materials and Methods

The leaves of 4 species of *Dracaena* were collected from PN Mehra botanical garden in Panjab University, Chandigarh. DNA barcoding was done at public DNA facility at Rajiv Gandhi Centre for Biotechnology, Thiruvananthapuram, India. Genomic DNA was extracted using the NucleoSpin® Plant II Kit (Macherey-Nagel) according to the manufacturer's protocol. The quality of the extracted DNA was assessed by agarose gel electrophoresis. The purified genomic DNA was subsequently used as a template for amplification of the *rbcL* and *trnL* DNA barcode regions. PCR amplification of target DNA barcode region was performed using Phire PCR kit, following manufacturers' protocol. The oligonucleotide sequence of PCR primers for DNA barcode region, RBCL and TRNL as follows

RBCL-AF(Forward)  
ATGTCACCACAAACAGAGACTAAAGC  
RBCL-724R(Reverse)  
TCGCATGTACCTGCAGTAGC  
trnLF-F-A50272(Forward)  
TCCTCCGCTTATTGATATGC  
trnLF-E-B49873(Reverse)  
GGAAGTAAAAGTCGTAACAAGG

PCR amplification was performed using a GeneAmp PCR System 9700 thermal cycler (Applied Biosystems). The thermal cycling conditions followed standard DNA barcoding protocols (Kress, 2007). The PCR program included an initial denaturation at 98 °C for 30 s, followed by 40 cycles consisting of denaturation at 98 °C for 5 s, annealing at 58 °C for 10 s, and extension at 72 °C for 15 s, with a final extension at 72 °C for 1 min. The amplified products were assessed using a NanoDrop spectrophotometer and agarose gel electrophoresis, and subsequently stored at 4 °C until sequencing. Bidirectional (forward and reverse) Sanger sequencing of the *rbcL* and *trnL* markers was carried out at the Rajiv Gandhi Centre for Biotechnology.

The generated DNA barcode sequences were deposited in the Barcode of Life Database (BOLD) (Ratnasingham, 2007). Sequences accepted by BOLD as valid barcodes were subsequently submitted to GenBank with the "BARCODE" keyword (Liu, 2012). Sequence similarity searches were performed using the BLAST alignment tool (Altschul et al., 1990). Multiple sequence alignment (MSA) was carried out using the Clustal Omega algorithm implemented in the EMBL-EBI Job Dispatcher sequence analysis platform (CLUSTAL O v1.2.4) (Madeira et al., 2024).

### Results And Discussion

The genus *Dracaena* is now large and diverse because of the inclusion of the species of genus *Sansevieria* and *Pleomele*. These species include *Dracaena trifasciata* (Prain) Mabb. (*Sansevieria trifasciata* Prain) *Dracaena kirkii* Baker (Syn. *Pleomele kirkii* (Baker) N. E. Br.), *Dracaena zeylanica* (L.) Mabb. (Syn. *Sansevieria zeylanica* (L.) Willd), and *Dracaena angolensis* (Welw.) Byng & Christenh. (Syn. *Sansevieria cylindrica*

Bojer ex Hook. Plant species, including even the species of genus *Dracaena* have been basically identified by studying their morphological features. *Dracaena trifasciata* is commonly known as Mother-in-law's tongue and Snake plant also. The sword-shaped leaves are hard, thick, erect, smooth, and acute. The dark green leaves have been marked with the white stripes. The leaf size may be up to one meter (Babu, 2024).

Later on, the anatomical, biochemical, palynological etc. approaches have also been practiced for the species identification. Pollen morphology of 15 species of genus *Sansevieria* through Scanning Electron Microscopy (SEM) could not establish the identity of all the species but has categorized them into groups (Klimko, 2017). However, their observation can be used to differentiate between the species of a closely related genus *Dracaena*. However, it is not always possible to identify the species precisely using these methodologies due to the resemblances and complexity in these characters. Now the researchers are using the DNA barcoding to differentiate the morphologically similar species. The taxonomic characterization of several *Dracaena* species is quite difficult, especially which are growing in Asia. Any misidentification of medicinal plant species including *Dracaena* can severely affect the pharmaceutical preparations. Therefore, the correct identification of the species is highly required.

DNA barcoding using primers targeting the *rbcL* gene was successfully completed, and the resulting data were deposited in the Barcode of Life Database (BOLD). The *rbcl* DNA barcode sequences on BOLD portal are available against process ID SDP850114-25 for *Dracaena cylindrica*, SDP850115-25 for *Dracaena trifasciata*, SDP850116-25 for *Dracaena zeylanica*,

and SDP850118-25 for *Dracaena kirkii*. DNA sequences accepted by BOLD as valid barcodes were subsequently deposited in GenBank with the "BARCODE" tag. The BOLD database does not accept *trnL* sequences as standard barcode, so they are deposited to GenBank. The GenBank ID for respectively *trnL* DNA barcode sequences of *Dracaena zeylanica* is PV450433, for *D. trifasciata* its PV450434, for *D. cylindrica* its PV450432, for *D. kirkii* its PV450431.

There is not a significant difference in the DNA barcode of these species, however they could be clearly identified based on morphological characterization. Through multiple sequence alignment it was found that the only difference in the *rbcL* DNA barcode of four *Dracaena* species is that at position 553, *D. kirkii* and *D. cylindrica* has A, whereas *D. trifasciata* and *D. zeylanica* has C. Multiple sequence alignment of *trnL* sequence of the four species revealed only minor differences. In the *trnL* sequence of *D. zeylanica*, at position 317 has A and all others have G. At position 335 in *D. zeylanica* and *D. cylindrica* is G whereas *D. trifasciata* and *D. kirkii* have A. At position 259 in *D. cylindrica* is A, but in all other its G, At position 289 in *D. cylindrica* is T but in all other its C. The *matK* sequence also could not distinguish these species but detailed sequence data are not reported here because good quality of sequence for all these species in forward and reverse direction could not be produced.

The TRNL and RBCL sequences of respective species were concatenated and used for multiple sequence alignment. A phylogenetic tree was drawn using this MSA (multiple sequence

alignment) figure 1 (a, b). Thus, it is concluded that DNA barcoding using the *rbcL* and *trnL* markers was unable to clearly differentiate the four species, which were otherwise reliably distinguished based on morphological characters.

Phylogenetic issues can be often resolved successfully using plant DNA barcoding (Kulikovskiy, 2016). However, in certain cases, DNA barcoding has been unsuccessful or only partially effective in distinguishing closely related plant species, such as *Cinnamomum* (Chandrasekara et al., 2021), *Calligonum* (Li et al., 2014), and *Lysimachia* (Zhang et al., 2012). The performance of DNA barcode markers may vary across plant groups, with markers proving effective in some taxa but failing in others (Liu et al., 2011). Roy et al. (2010) have also suggested that DNA barcoding may not be suitable for resolving species boundaries within taxonomically complex plant groups. Consistent with these observations, the results of the present study using the *rbcL* and *trnL* markers indicate that *Dracaena* species exhibit limited sequence divergence at these barcode loci.

The four species of *Dracaena* can be identified based on the leaf morphology and color pattern (figure 2). As name suggest, *Dracaena cylindrica* has cylindrical leaves, *Dracaena trifasciata* leaves has three vertical color bands, *Dracaena kirkii* (*Dracaena pathera*) has very hard leaves, *Dracaena zeylanica* has leaves with some wavy horizontal patch of white or light green color (Chahinian, 2005; Graf, 1976; Harrison, 2012). The following table 1 lists the morphological features of the four *Dracaena* species studied:

**Table 1: Morphological differences in four species of genus *Dracaena*.**

| Feature          | <i>Dracaena trifasciata</i>  | <i>Dracaena kirkii</i>  | <i>Dracaena cylindrica</i>                     | <i>Dracaena zeylanica</i>   |
|------------------|--|---|--|---|
| Leaf Shape       | Flat, sword-shaped leaves  | Strap shaped leaves with wavy edges                           | Cylindrical, rod-like leaves                   | Flat, strap-shaped leaves   |
| Leaf Arrangement | Grows vertically from a basal rosette  | Forms a rosette with multiple leaves                          | Fan-shaped arrangement from a basal rosette    | Forms a rosette with multiple leaves  |
| Leaf Size        | Typically 70–100 cm long, 5–7 cm wide  | Typically 70–100 cm long, 8–11 cm wide                        | Up to 150 cm tall, 2–3 cm in wide              | Typically 100-120 cm long, 7-9 cm wide                                      |
| Leaf Coloration  | Leaf blade has 3 vertical color band, yellow on both edges and green in middle, the middle green part has horizontal light green or white wavy stripes | Dull green color with yellowish-brown horizontal wavy stripes | Light green with horizontal dark green stripes | Bright green color with light green or white -brown horizontal wavy stripes |
| Leaf Texture     | Stiff and upright  | Very stiff and rough  | Stiff, smooth, and leathery                    | Smooth and slightly narrower at the base                                    |

While searching BOLD database, the *rbcl* sequence of these 4 species matched 99% with species *Maianthemum racemosum* because that was the closest species available in BOLD database. Therefore, now submitting these *rbcl* sequences in BOLD database will help in identification of *Dracaena* species for medicinal and forensic applications.

### Conclusion

DNA barcoding using the *rbcl* and *trnL* gene markers did not effectively differentiate among *Dracaena* species. Generally, DNA barcode of

species of a genus has difference equal to 5% or more for standard DNA barcode genes like *rbcl*, *MatK*, *trnL*, but such exceptions are there and some scientists also propose new DNA barcoding makers for plants like ITS, *ycf1*, and *psbA* etc. Therefore, sometimes DNA barcoding has to be corroborated with morphological tools for differentiation between species. In the present study, the *rbcl* and *trnL* DNA barcode sequences showed little variation among *Dracaena* species, whereas morphological characters—particularly leaf shape, colour pattern, and leaf hardness—clearly differentiated the species. *Dracaena*

*zeylanica* has leaves with a pattern of wavy white patches, *Dracaena cylindrica* has cylindrical shape leaves with no color pattern, *Dracaena trifasciata* leaves with 3 vertical color bands, *Dracaena kirkii* has very hard leaves with a pattern of wavy grey patches.

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#### Compliance with Ethical Standards

The authors declare that they have no conflicts of interest. This article does not contain any studies involving animals or human participants.

**Author Contribution:** Conceptualization, [JR]; investigation, [GM, HP, GS, NS, PM, AJ, AS]; writing – review and editing, [JR]

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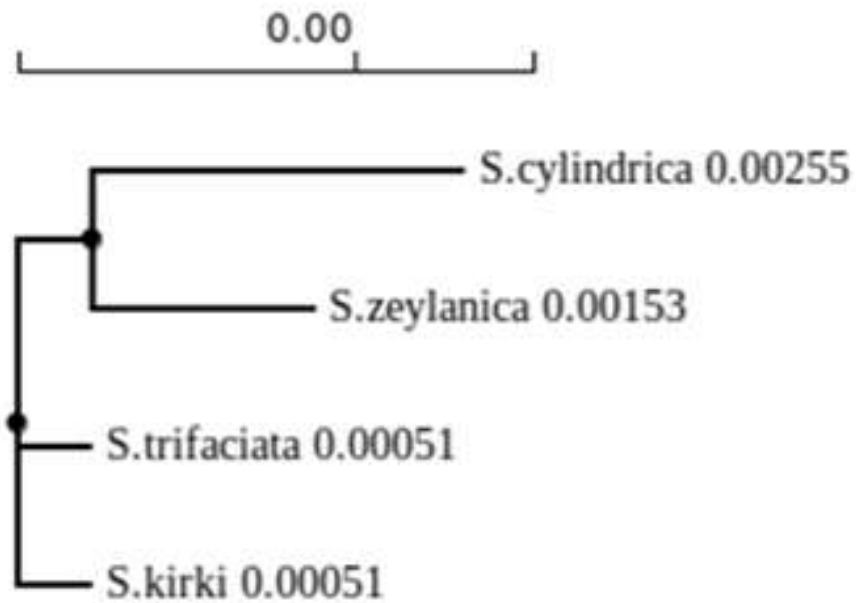
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|                      |   |     |
|----------------------|---|-----|
| <i>S. cylindrica</i> | TATCCCGACCATTTCCCGCGCATCATACTAGCGGAGTACTTGTATCTATGGAAATTACAT  | 60  |
| <i>S. zeylanica</i>  | TATCCCGACCATTTCCCGCGCATCATACTAGCGGAGTACTTGTATCTATGGAAATTACAT  | 60  |
| <i>S. trifaciata</i> | TATCCCGACCATTTCCCGCGCATCATACTAGCGGAGTACTTGTATCTATGGAAATTACAT  | 60  |
| <i>S. kirki</i>      | TATCCCGACCATTTCCCGCGCATCATACTAGCGGAGTACTTGTATCTATGGAAATTACAT  | 60  |
|                      | *****   |     |
| <i>S. cylindrica</i> | AGACTCAAAAAAGTATTCAAAAATTTGACCTAGTCCCCGAATTTCTTCGATCTTCAAAAA  | 120 |
| <i>S. zeylanica</i>  | AGACTCAAAAAAGTATTCAAAAATTTGACCTAGTCCCCGAATTTCTTCGATCTTCAAAAA  | 120 |
| <i>S. trifaciata</i> | AGACTCAAAAAAGTATTCAAAAATTTGACCTAGTCCCCGAATTTCTTCGATCTTCAAAAA  | 120 |
| <i>S. kirki</i>      | AGACTCAAAAAAGTATTCAAAAATTTGACCTAGTCCCCGAATTTCTTCGATCTTCAAAAA  | 120 |
|                      | *****   |     |
| <i>S. cylindrica</i> | GAAGACTTTCTTTTTGAATGTAAGTAGTAAGTGATATGGACTTCAATTATATATGTTTAT  | 180 |
| <i>S. zeylanica</i>  | GAAGACTTTCTTTTTGAATGTAAGTAGTAAGTGATATGGACTTCAATTATATATGTTTAT  | 180 |
| <i>S. trifaciata</i> | GAAGACTTTCTTTTTGAATGTAAGTAGTAAGTGATATGGACTTCAATTATATATGTTTAT  | 180 |
| <i>S. kirki</i>      | GAAGACTTTCTTTTTGAATGTAAGTAGTAAGTGATATGGACTTCAATTATATATGTTTAT  | 180 |
|                      | *****   |     |
| <i>S. cylindrica</i> | TTGTACAGGTATCGTATCTATTCAAACCAAATTAGGATAAGATCAAAGATTTCTGTTTCG  | 240 |
| <i>S. zeylanica</i>  | TTGTACAGGTATCGTATCTATTCAAACCAAATTAGGATAAGATCAAAGATTTCTGTTTCG  | 240 |
| <i>S. trifaciata</i> | TTGTACAGGTATCGTATCTATTCAAACCAAATTAGGATAAGATCAAAGATTTCTGTTTCG  | 240 |
| <i>S. kirki</i>      | TTGTACAGGTATCGTATCTATTCAAACCAAATTAGGATAAGATCAAAGATTTCTGTTTCG  | 240 |
|                      | *****   |     |
| <i>S. cylindrica</i> | GATCCGTTTGTGAAAGAAGTAGAATGAATGAGAAAGATATTGAATTTCCCTTGAACCTCTT | 300 |
| <i>S. zeylanica</i>  | GATCCGTTTGTGAAAGAAGTAGAATGAATGAGAAAGATATTGAATTTCCCTTGAACCTCTT | 300 |
| <i>S. trifaciata</i> | GATCCGTTTGTGAAAGAAGTAGAATGAATGAGAAAGATATTGAATTTCCCTTGAACCTCTT | 300 |
| <i>S. kirki</i>      | GATCCGTTTGTGAAAGAAGTAGAATGAATGAGAAAGATATTGAATTTCCCTTGAACCTCTT | 300 |
|                      | *****   |     |
| <i>S. cylindrica</i> | ATGAAAAAAAAAAGAGAATAACTAAATAGGTAAAGTAAAATGGGCTTTTTATTGGGG     | 360 |
| <i>S. zeylanica</i>  | ATGAAAAAAAAAAGAGAATAACTAAATAGGTAAAGTAAAATGGGCTTTTTATTGGGG     | 360 |
| <i>S. trifaciata</i> | ATGAAAAAAAAAAGAGAATAACTAAATAGGTAAAGTAAAATGGGCTTTTTATTGGGG     | 360 |
| <i>S. kirki</i>      | ATGAAAAAAAAAAGAGAATAACTAAATAGGTAAAGTAAAATGGGCTTTTTATTGGGG     | 360 |
|                      | *****   |     |
| <i>S. cylindrica</i> | ATAGAGTTATTATACTCCTGATTACGAAACCAAAGATACTGATATCTTGGCAGCATTCCG  | 420 |
| <i>S. zeylanica</i>  | ATAGAGTTATTATACTCCTGATTACGAAACCAAAGATACTGATATCTTGGCAGCATTCCG  | 420 |
| <i>S. trifaciata</i> | ATAGAGTTATTATACTCCTGATTACGAAACCAAAGATACTGATATCTTGGCAGCATTCCG  | 420 |
| <i>S. kirki</i>      | ATAGAGTTATTATACTCCTGATTACGAAACCAAAGATACTGATATCTTGGCAGCATTCCG  | 420 |
|                      | *****   |     |
| <i>S. cylindrica</i> | AGTAACTCCTCAACCCGAGTTCCTCGTGAAGAAGCAGGGCTGCGGTAGCTGCCGAATC    | 480 |
| <i>S. zeylanica</i>  | AGTAACTCCTCAACCCGAGTTCCTCGTGAAGAAGCAGGGCTGCGGTAGCTGCCGAATC    | 480 |
| <i>S. trifaciata</i> | AGTAACTCCTCAACCCGAGTTCCTCGTGAAGAAGCAGGGCTGCGGTAGCTGCCGAATC    | 480 |
| <i>S. kirki</i>      | AGTAACTCCTCAACCCGAGTTCCTCGTGAAGAAGCAGGGCTGCGGTAGCTGCCGAATC    | 480 |
|                      | *****   |     |
| <i>S. cylindrica</i> | CTCTACTGGTACATGGACAACCTGTGTGGACTGATGGACTTACCAGTCTTGATCGTTACAA | 540 |
| <i>S. zeylanica</i>  | CTCTACTGGTACATGGACAACCTGTGTGGACTGATGGACTTACCAGTCTTGATCGTTACAA | 540 |
| <i>S. trifaciata</i> | CTCTACTGGTACATGGACAACCTGTGTGGACTGATGGACTTACCAGTCTTGATCGTTACAA | 540 |
| <i>S. kirki</i>      | CTCTACTGGTACATGGACAACCTGTGTGGACTGATGGACTTACCAGTCTTGATCGTTACAA | 540 |
|                      | *****   |     |

|                      |   |     |
|----------------------|---|-----|
| <i>S. cylindrica</i> | AGGACGATGCTACCACATTGAGCCGTTGTTGGGAAGAAAATCAATATATTTGTTATGT    | 600 |
| <i>S. zeylanica</i>  | AGGACGATGCTACCACATTGAGCCGTTGTTGGGAAGAAAATCAATATATTTGTTATGT    | 600 |
| <i>S. trifaciata</i> | AGGACGATGCTACCACATTGAGCCGTTGTTGGGAAGAAAATCAATATATTTGTTATGT    | 600 |
| <i>S. kirki</i>      | AGGACGATGCTACCACATTGAGCCGTTGTTGGGAAGAAAATCAATATATTTGTTATGT    | 600 |
|                      | *****   |     |
| <i>S. cylindrica</i> | AGCTTATCCTTTAGACCTTTTTGAAGAAGGTTCTGTTACTAACATGTTTACTTCCATTGT  | 660 |
| <i>S. zeylanica</i>  | AGCTTATCCTTTAGACCTTTTTGAAGAAGGTTCTGTTACTAACATGTTTACTTCCATTGT  | 660 |
| <i>S. trifaciata</i> | AGCTTATCCTTTAGACCTTTTTGAAGAAGGTTCTGTTACTAACATGTTTACTTCCATTGT  | 660 |
| <i>S. kirki</i>      | AGCTTATCCTTTAGACCTTTTTGAAGAAGGTTCTGTTACTAACATGTTTACTTCCATTGT  | 660 |
|                      | *****   |     |
| <i>S. cylindrica</i> | GGGTAATGTATTTGGTTTCAAAGCCCTACGAGCTCTACGTCTGGAGGATCTGCGAATTCC  | 720 |
| <i>S. zeylanica</i>  | GGGTAATGTATTTGGTTTCAAAGCCCTACGAGCTCTACGTCTGGAGGATCTGCGAATTCC  | 720 |
| <i>S. trifaciata</i> | GGGTAATGTATTTGGTTTCAAAGCCCTACGAGCTCTACGTCTGGAGGATCTGCGAATTCC  | 720 |
| <i>S. kirki</i>      | GGGTAATGTATTTGGTTTCAAAGCCCTACGAGCTCTACGTCTGGAGGATCTGCGAATTCC  | 720 |
|                      | *****   |     |
| <i>S. cylindrica</i> | CCCTGCTTATACCAAAACTTTCCTAGGCCCGCCTCATGGCATCCAATCTGAAAGAGATAA  | 780 |
| <i>S. zeylanica</i>  | CCCTGCTTATACCAAAACTTTCCTAGGCCCGCCTCATGGCATCCAATCTGAAAGAGATAA  | 780 |
| <i>S. trifaciata</i> | CCCTGCTTATACCAAAACTTTCCTAGGCCCGCCTCATGGCATCCAATCTGAAAGAGATAA  | 780 |
| <i>S. kirki</i>      | CCCTGCTTATACCAAAACTTTCCTAGGCCCGCCTCATGGCATCCAATCTGAAAGAGATAA  | 780 |
|                      | *****   |     |
| <i>S. cylindrica</i> | ATTGAACAAGTATGGTCGTCCCTATTGGGATGACTATTAACCAAAATTGGGATTATC     | 840 |
| <i>S. zeylanica</i>  | ATTGAACAAGTATGGTCGTCCCTATTGGGATGACTATTAACCAAAATTGGGATTATC     | 840 |
| <i>S. trifaciata</i> | ATTGAACAAGTATGGTCGTCCCTATTGGGATGACTATTAACCAAAATTGGGATTATC     | 840 |
| <i>S. kirki</i>      | ATTGAACAAGTATGGTCGTCCCTATTGGGATGACTATTAACCAAAATTGGGATTATC     | 840 |
|                      | *****   |     |
| <i>S. cylindrica</i> | CGCAAAAACACTACGGTAGAGCGGTTTATGAATGTCTACGCGGTGGACTTGATTTTACCAA | 900 |
| <i>S. zeylanica</i>  | CGCAAAAACACTACGGTAGAGCGGTTTATGAATGTCTCCGCGGTGGACTTGATTTTACCAA | 900 |
| <i>S. trifaciata</i> | CGCAAAAACACTACGGTAGAGCGGTTTATGAATGTCTCCGCGGTGGACTTGATTTTACCAA | 900 |
| <i>S. kirki</i>      | CGCAAAAACACTACGGTAGAGCGGTTTATGAATGTCTACGCGGTGGACTTGATTTTACCAA | 900 |
|                      | *****   |     |
| <i>S. cylindrica</i> | GGATGATGAAAACGTGAACTCACAACCTTTTATGCGTTGGAGAGACCGTTTCTTATTTTG  | 960 |
| <i>S. zeylanica</i>  | GGATGATGAAAACGTGAACTCACAACCTTTTATGCGTTGGAGAGACCGTTTCTTATTTTG  | 960 |
| <i>S. trifaciata</i> | GGATGATGAAAACGTGAACTCACAACCTTTTATGCGTTGGAGAGACCGTTTCTTATTTTG  | 960 |
| <i>S. kirki</i>      | GGATGATGAAAACGTGAACTCACAACCTTTTATGCGTTGGAGAGACCGTTTCTTATTTTG  | 960 |
|                      | *****   |     |
| <i>S. cylindrica</i> | TGCTGAAGCACTTTTAAA  | 979 |
| <i>S. zeylanica</i>  | TGCTGAAGCACTTTTAAA  | 979 |
| <i>S. trifaciata</i> | TGCTGAAGCACTTTTAAA  | 979 |
| <i>S. kirki</i>      | TGCTGAAGCACTTTTAAA  | 979 |
|                      | *****   |     |



(b)

**Figure 1 (a)** The first 366 nucleotides are TRNL sequence (purple colored asterisks in row 5), the remaining 613 nucleotides are rbcL sequence of respective species DNA barcode that was also deposited in BOLD (barcode of life database). The MSA multiple sequence alignment of this concatenated TRNL-rbcL sequence was used to draw phylogenetic tree given in b. (b) Phylogenetic tree



(a) *Dracaena cylindrica*



(b) *Dracaena kirkii*



(c) *Dracaena zylanica*



(d) *Dracaena trifasciata*

**Figure 2 (a-d): Differences in color and morphology of leaves of *Dracaena* species.**

## **MORPHOLOGICAL AND DNA BARCODING BASED IDENTIFICATION...**

# **HERBAL MEDICINE AS A THERAPY FOR CANCER: A SCIENTOMETRIC ANALYSIS OF THE SCOPUS DATABASE DURING THE PERIOD 2015- 2025**

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## **Abstract**

The foremost health challenge globally is cancer impelling increase in scientific inclination towards natural and plant based therapeutic substitutes. The paper analysis the research publications output on Herbal Medicine used as a Therapy for Cancer. In the study the publication data was sources from the Scopus database covering the ten year period 2015 to 2025. A total 561 research documents were retrieved with 12118 citations from all over the world. The highest number of publications (18.36 percent) was contributed in 2024, followed by 13.90 percent and 13.01 percent publications in 2025 and 2023, respectively. The average number of publications per year is 51. Frontiers in Pharmacology, Switzerland, contributed a maximum of 26 documents (20.5 percent) during the past 10 years. Though China and India have the highest number of research papers, the average citation per paper is significantly low (7.51 and 13.85).

**Keywords:** Scientometric, Relative citation index, Relative growth rate, Degree of collaboration, Herbal Medicine, Cancer Therapy, Collaborative index

## **Introduction**

Natural products and herbal extracts have long been used in traditional healthcare systems such as traditional Chinese and Ayurveda for treating various ailments (Ghate et al., 2013, 2014, and 2016). Herbal medicines have gained significant attention in cancer therapy. Several research studies demonstrate their benefits in anticancer outcomes. The global increase in cancer incidence has positioned cancer as the second leading cause of death, with 20 million new cases and around 10 million deaths in 2022 (Bray, 2024). These breakthroughs have made herbal agents more effective and safer for clinical use. Herbal medicines (Newman and Cragg, 2007)

also play a vital role in drug discovery for human diseases. Additionally, alternative medicine remains popular, with Saira and Sultan (2025) reporting that 70% of the global population prefers its use in primary healthcare. Herbal extracts and medicines are widely recognised as effective and safe.

Scientific productivity is significant for society, which is measured by publications and citation data (Surulinathi et al., 2021). The rapid development of herbal medicine in cancer research made it imperative to understand the most productive contributors, journals, subjects, and countries, and to remain updated on the latest

knowledge. The performance analysis technique is employed, which signifies the indicators of the subject's research output (the number of publications and citations) and identifies predominant research elements (top-cited papers and top productive sources).

### Previous studies

A study by KK and M (2025) reported the blooming global prominence of plant-based anticancer compounds. The study calls on researchers to design rendition studies, funding bodies to prioritize grants, and policymakers to support frameworks that advance natural product oncology, ultimately accelerating the development of effective therapies for cancer patients. There is a progressive development in publications and Citation score in the field of herbal drugs, medicines, and vaccines. The countries with the highest number of recorded citations in the field are the USA, China, UK, Germany, and India (Surulinathi, Jayasuriya, Duraipandi, & Senthamilselvi, 2021).

The Web of Science analysis revealed that the annual increase in publications and the United Nations remains at the top for research on natural products as therapy for cancer (Chen, Li, Zhang, Yao, and Guo, 2021). The study by Ankamah, Addo, and Bekoe (2025) indicated that publications are increasing steadily in this field of knowledge, and the most potent source is 'the Journal of Ethnopharmacology (JEP)' with 116 articles (10.23%) share. Li and Chen's (2025) study reported increasing growth in the research area of traditional Chinese Medicine in treating cancer through immune system regulation. Their study revealed that China was ranked first as it

has the highest number of publications and diligently collaborates internationally. A total of 2,648 publications from 8,782 institutions by 297 countries were published, where China and the United States of America lead among all (Li, Cui, Shao, Kang, and Yan, 2025). The prominent country with the highest 89 publications is China, followed by 34 publications from Brazil, India (30), and 28 publications by the USA (Li, Kreher, and Schmalz, 2025).

Another study by Benomar et al. (2025) reported significant progress in pharmaceutical quality control of medicinal plants since 2013. There was an increase in national and international collaboration with China, Brazil, Korea, and India. Nabilolahi et al. (2025) found that the scientific productivity of Iranian traditional medicine is growing continuously. It remained at its peak in 2021, with 1893 document publications and 14383 citations received in 2014. Ji et al. (2025) studied acupuncture for cancer over the past 20 years. The study revealed that 7 out of 10 institutions were from the USA, and the journal 'Integrative Cancer Therapies' has published the highest research. In 2024, M, KK, and Vitthal's study concluded that Banaras Hindu University, Jamia Millia Islamia, and Savitribai Phule Pune University are the prominent contributors in the area of medicinal plants and collaborated with the USA, China, and South Korea. The annual rate over the time of document production declines (29.65%) (Alvitez-Temoche et al., 2025). The number of (Qu et al. 2025) annual publications is increasing from 2 to 37. China ranks first with 144 articles and 2678 citations, closely followed by the USA with 83 publications and 3732 citations.

It has been observed while reviewing the literature that several research studies have been published on the concept of scientometrics. However, there's no comprehensive study on the topic of herbal medicine as a Therapy for Cancer, which incited the researchers to select this topic.

### Objectives

The objectives set for the study are:

1. To examine the growth of Herbal Medicine used as a Therapy for Cancer research output from 2015 to 2025.
2. To analyze the country, subject, and document type research on Herbal Medicine used as a Therapy for Cancer.
3. To find out the authors and journals in the field of Herbal Medicine used as a Therapy for Cancer.
4. To examine the highly cited papers on research in Herbal Medicine used as a Therapy for Cancer.

### Research methodology

The study analyzes Scopus data on Herbal Medicine as Cancer Therapy from 2015 to 2025, using scientometric indicators. Data was collected on 13 October 2025 and analyzed in Microsoft Excel. The main search used the keywords "herbal medicine" AND "cancer therapy," yielding 1,115 documents. Results were then limited to Herbal Medicine and Cancer Therapy, Review, Article, Conference Paper, Book Chapter, English language, and 2015-2025. Citation data was collected up to 13 October 2025. After applying these limits, 561 documents remained for analysis. The used string for the study is:

TITLE-ABS-KEY ("herbal medicine" AND "cancer therapy") AND PUBYEAR > 2014 AND PUBYEAR < 2026 AND ( LIMIT-TO (EXACTKEYWORD , "Herbal Medicine" ) OR LIMIT-TO (EXACTKEYWORD, "Cancer Therapy" ) ) AND ( LIMIT-TO ( DOCTYPE , "ch" ) OR LIMIT-TO ( DOCTYPE , "cp" ) OR LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO (DOCTYPE, "re")) AND (LIMIT-TO (LANGUAGE , "English" ) )

In this study, Microsoft Office Excel (v.2016) was used to analyse the data. The study has analysed the data with percentage method. Moreover, authors used scientometric indicators - Citations per Publication (CPP), H-Index and Relative Citation Index (RCI). The formula for assessing the impact of Herbal Medicine used as a Therapy for Cancer's research publications for the years, countries, institutes, and authors is:

$$CPP = \frac{\text{Total Citations of a Country or Institution}}{\text{Total of Publications}}$$

Moreover, the formula to measure both influence and visibility of a country's research global wise is:

$$RCI = \frac{\text{A Country share of the World Citations}}{\text{A Country share of the World Publications}}$$

RCI = 1 indicates that a country's citation rate is equal to the world citation rate

RCI > 1 indicates that a country's citation rate is greater than the world citation rate

RCI < 1 indicate that a country's citation rate is lower than the world citation rate

Furthermore, the study measured the h-index by examining researchers' publication lists and

citation counts. Assessing the h-index provides insight into both the impact and the quantity and quality of scientific output.

**Interpretations and Findings**

**Document Type**

Document types are identifies during the ten-year

study period of 2015-2025 on Herbal Medicine used as a Therapy for Cancer Research publications are shown in Table 1. It was noted that a maximum of 303 (54.04 per cent) Research publications are contributed by Review, followed by 251 (44.74 per cent) research publications are Article and 7 (1.25 per cent) are book chapter.

**Table 1:** Document Type

| Sr. No. | Document Type | TP  | %     | Citations | %     |
|---------|---------------|-----|-------|-----------|-------|
| 1.      | Review        | 303 | 54.01 | 9117      | 68.45 |
| 2.      | Article       | 251 | 44.74 | 4189      | 31.45 |
| 3.      | Book Chapter  | 7   | 1.25  | 14        | 0.10  |
| Total   |               | 561 | 100   | 13320     | 100   |

The study confirmed that an almost equal number of research publications are Reviews and Articles. The Review has the highest citations, i.e, 9117 (68.45 per cent). However, the combined score of articles and book chapters received 4203 (31.55 per cent) citations.

**Publication Output and Citations Count in Herbal Medicine used as a Therapy for Cancer**

**Research Publications**

Table 2 presents the number of research publications and citations for studies on Herbal Medicine as a therapy in Cancer research from 2015 to 2025. In this period, there are 561 publications, 12,118 citations, and an h-index of 51.

**Table 2:** Publication Output and Citations Count in Herbal Medicine used as a Therapy for Cancer Research Publications

| Sr. No. | Year | Total Publications | %    | TC | %    | Cited | %    | CPP  | RCI  |
|---------|------|--------------------|------|----|------|-------|------|------|------|
| 1.      | 2015 | 24                 | 4.28 | 1  | 0.01 | 1043  | 7.83 | 0.04 | 0.00 |
| 2.      | 2016 | 28                 | 5.00 | 35 | 0.29 | 1073  | 8.06 | 1.25 | 0.06 |

|       |      |     |       |       |       |        |       |                    |                  |
|-------|------|-----|-------|-------|-------|--------|-------|--------------------|------------------|
| 3.    | 2017 | 26  | 4.63  | 108   | 0.89  | 641    | 4.81  | 4.15               | 0.19             |
| 4.    | 2018 | 39  | 6.95  | 202   | 1.67  | 2374   | 17.82 | 5.18               | 0.24             |
| 5.    | 2019 | 31  | 5.53  | 431   | 3.56  | 2004   | 15.04 | 13.9               | 0.64             |
| 6.    | 2020 | 59  | 10.52 | 809   | 6.68  | 2109   | 15.83 | 13.71              | 0.63             |
| 7.    | 2021 | 45  | 8.02  | 1380  | 11.39 | 768    | 5.77  | 30.67              | 1.42             |
| 8.    | 2022 | 55  | 9.80  | 1735  | 14.31 | 1235   | 9.27  | 31.55              | 1.46             |
| 9.    | 2023 | 73  | 13.01 | 1972  | 16.27 | 1041   | 7.81  | 27.01              | 1.25             |
| 10.   | 2024 | 103 | 18.36 | 2555  | 21.08 | 886    | 6.65  | 24.80              | 1.15             |
| 11.   | 2025 | 78  | 13.90 | 2890  | 23.85 | 146    | 1.11  | 37.05              | 1.72             |
| Total |      | 561 | 100   | 12118 | 100   | 13,320 | 100   | 17.21<br>(average) | 0.8<br>(average) |

\*CPP=Citations per count, RCI- Relative Citation Index

The highest number, i.e., 103 (18.36 percent) of publications, was contributed in 2024, followed by 78 (13.90 percent) and 73 (13.01 percent) publications in 2025 and 2023, respectively. The average number of publications per year is 51. Of the 12,118 citations referenced in the annual publication data breakdown, 78 publications in 2025 received 2,890 (23.85%) citations, and 103 publications in 2024 received 2,555 (21.08%) citations. The study also noted that, altogether, a total of 561 publications have collectively garnered 13,320 citations across all years. The maximum citation per paper was 37.05 in 2025, followed by 31.55 in 2022 and 30.67 in 2023. The average number of citations per paper is 17.21. The maximum RCI is 1.72 in 2025, followed by 1.46 in 2022 and 1.42 in 2021. The average RCI is 0.796.

### Leading Prolific Sources

Table 3 illustrates the most productive journals on the selected topic of the study. The analysis reveals that *Frontiers in Pharmacology, Switzerland*, contributed a maximum of 26 documents (20.5 percent) during the past 10 years, followed closely by 24 documents (18.9 percent) by *Integrative Cancer Therapies, Thousand Oaks, CA*. However, the other eight journals from the list of top 10 most prolific sources contributed 7-12 research publications (6.0 - 9.5 percent). It was further observed that the highest citations received were 429 (16.0 percent) on 11 documents by *Evidence-Based Complementary and Alternative Medicine, USA*. This is followed by the journal *Biomedicine and Pharmacotherapy, Paris*, which has 393 (14.0 percent) citations on 9 documents and 371 (14.0 percent) on 11 documents with *Anti Cancer Agents in Medicinal Chemistry, UAE*.

**Table 3:** Top 10 most prolific sources

| Sr. No. | Source Title   | TP  | %    | TC   | %    | CPP   | HI | RCI  | Cite score |
|---------|--|-----|------|------|------|-------|----|------|------------|
| 1.      | Frontiers in Pharmacology, Switzerland                     | 26  | 20.5 | 340  | 12.0 | 13.07 | 12 | 0.59 | 8.9        |
| 2.      | Integrative Cancer Therapies, Thousand Oaks, CA            | 24  | 18.9 | 277  | 10.0 | 11.54 | 10 | 0.53 | 4.8        |
| 3.      | Journal of Ethno-pharmacology, Ireland                     | 12  | 9.5  | 282  | 10.0 | 23.5  | 8  | 1.05 | 10.4       |
| 4.      | Anti Cancer Agents in Medicinal Chemistry, UAE             | 11  | 8.7  | 371  | 14.0 | 33.73 | 7  | 1.61 | 5.8        |
| 5.      | Evidence Based Complementary and Alternative Medicine, USA | 11  | 8.7  | 429  | 16.0 | 39.0  | 9  | 1.84 | 3.5        |
| 6.      | Frontiers in Oncology, Switzerland                         | 11  | 8.7  | 233  | 9.0  | 21.18 | 7  | 1.03 | 6.9        |
| 7.      | Biomedicine and Pharmacotherapy, Paris                     | 9   | 7.0  | 393  | 14.0 | 43.71 | 8  | 2.0  | 12.8       |
| 8.      | Medicine United States                                     | 8   | 6.0  | 78   | 3.0  | 9.75  | 5  | 0.5  | 2.5        |
| 9.      | Pharmaceuticals, Basel, Switzerland                        | 8   | 6.0  | 200  | 7.0  | 25.0  | 6  | 1.16 | 7.7        |
| 10.     | Cancers, Basel, Switzerland                                | 7   | 6.0  | 149  | 5.0  | 21.28 | 8  | 0.83 | 8.8        |
| Total   |  | 127 | 100  | 2752 | 100  |       |    |      |            |

The study noted that the maximum citation per paper was 43.71 for Biomedicine and Pharmacotherapy, Paris, indicating a greater research impact per paper. Other notable sources include Evidence-Based Complementary and Alternative Medicine, USA, with a CPP 39.0 and Anti Cancer Agents in Medicinal Chemistry, UAE, having 33.73 CPP and CPP 25.0 for Pharmaceuticals, Basel, Switzerland, followed by Journal of Ethno-pharmacology (23.5 CPP), Ireland Frontiers in Oncology, Switzerland, and

Cancers, Basel, Switzerland (CPP above 21.2). Furthermore, five prolific sources have registered relative citation index above the world average of 1: Biomedicine and Pharmacotherapy, Paris (2.0); Evidence Based Complementary and Alternative Medicine, USA (1.84); Anti Cancer Agents in Medicinal Chemistry, UAE (1.61); Pharmaceuticals, Basel, Switzerland (1.16); Journal of Ethno-pharmacology, Ireland (1.05) and Frontiers in Oncology, Switzerland (1.03). The study also noted that Biomedicine and

Pharmacotherapy, Paris (12.8), has the highest citation score, followed by Journal of Ethnopharmacology, Ireland, that have a 10.4 citation score. Frontiers in Pharmacology, Switzerland, and Cancers, Basel, Switzerland, share an equal citation score (9.0).

### Documents per year by Author Name

The research productivity of the top 10 leading

authors in Herbal medicine research varied from 4 to 8 publications (Table 4). Global share of 10 authors is 9 percent (50 publications), and citation share is 13.5 percent (1634) from 2015 to 2025. The publications average per year is 5 per author: Ashrafizadeh, M. (8 papers), Sahebkar, A. (6 papers), Ahmadi, Z. (5 papers), Ben-Arye, E. (5 papers), Samarghandian, S. (5 papers), and Yoo, H.S. (5 papers).

**Table 4:** Scientometric profile of the most productive Authors

| S.r No.                      | Author Name       | TP  | %   | TC    | %   | CPP   | HI | RCI  |
|------------------------------|-------------------|-----|-----|-------|-----|-------|----|------|
| 1.                           | Ashrafizadeh, M.  | 8   | 16  | 358   | 22  | 44.75 | 8  | 1.37 |
| 2.                           | Sahebkar, A.      | 6   | 12  | 116   | 7   | 19.33 | 6  | 0.58 |
| 3.                           | Ahmadi, Z.        | 5   | 10  | 243   | 15  | 48.60 | 5  | 1.5  |
| 4.                           | Ben-Arye, E.      | 5   | 10  | 57    | 4   | 11.40 | 3  | 0.4  |
| 5.                           | Samarghandian, S. | 5   | 10  | 190   | 12  | 38.00 | 4  | 1.2  |
| 6.                           | Yoo, H.S.         | 5   | 10  | 33    | 2   | 6.60  | 3  | 0.2  |
| 7.                           | Cho, S.H.         | 4   | 8   | 102   | 6   | 25.50 | 3  | 0.75 |
| 8.                           | Farkhondeh, T.    | 4   | 8   | 168   | 10  | 42.00 | 4  | 1.25 |
| 9.                           | Kim, W.           | 4   | 8   | 102   | 6   | 25.50 | 4  | 0.75 |
| 10.                          | Mao, J.J.         | 4   | 8   | 265   | 16  | 66.25 | 4  | 2.0  |
| Total of 10 authors          |                   | 50  | 100 | 1634  | 100 | 32.8  |    | 1    |
| Total publications           |                   | 561 |     | 12118 |     | 17.21 |    | 0.8  |
| Share of 10 authors globally |                   | 9.0 |     | 13.5  |     |       |    |      |

The study observed that Ashrafizadeh, M. (358), Mao, J.J. (265), Ahmadi, Z. (243), and Samarghandian, S. (190) have received the highest number of citations, indicating eminent research publications. However, the H-Index is higher for authors: Ashrafizadeh, M. (8), Sahebkar, A. (6), and Ahmadi, Z. (5). Five authors registered citation impact per paper and relative citation index above the group average of 32.8 and 1: Mao, J.J. (66.25 and 2), Ahmadi, Z. (48.60 and 1.5), Ashrafizadeh, M (44 and 1.37),

Farkhondeh, T. (42 and 1.25), and Samarghandian, S. (38.0 and 1.2) during 2015-25.

### Leading Organizations

Table 5 highlights the most productive global affiliations in Herbal medicine research. The top ten organizations contributed 9 to 15 publications and 116 publications (20.7 per cent), global share. The global share of citations is 3290 (27.15 percent) during 2015-2025.

**Table 5:** Leading Organizations

| Sr. No.                                   | Organisations  | TP   | %    | TC    | %    | HI  | CPP               | RCI               |
|---|--|------|------|-------|------|-----|-------------------|-------------------|
| 1.  | Kyung Hee University, South Korea                              | 15   | 13.0 | 185   | 5.6  | 8   | 12.33             | 0.43              |
| 2.  | Ministry of Education of the People's Republic of China, China | 13   | 11.2 | 413   | 12.6 | 7   | 31.8              | 1.13              |
| 3.  | Tabriz University of Medical Sciences, Iran                    | 13   | 11.2 | 611   | 18.6 | 8   | 47.0              | 1.66              |
| 4.  | Shanghai University of Traditional Chinese Medicine, China     | 12   | 10.3 | 259   | 8    | 9   | 21.58             | 0.78              |
| 5.  | Shahid Beheshti University of Medical Sciences, Iran           | 12   | 10.3 | 272   | 8    | 5   | 22.66             | 0.78              |
| 6.  | China Academy of Chinese Medical Sciences, China               | 12   | 10.3 | 224   | 7    | 9   | 18.66             | 0.68              |
| 7.  | Guangzhou University of Chinese Medicine, China                | 12   | 10.3 | 460   | 14   | 7   | 38.33             | 1.36              |
| 8.  | Mashhad University of Medical Sciences, Iran                   | 9    | 7.8  | 146   | 4.4  | 8   | 16.22             | 0.56              |
| 9.  | Harvard Medical School, Boston                                 | 9    | 7.8  | 404   | 12.2 | 9   | 44.88             | 1.56              |
| 10.                                       | Memorial Sloan-Kettering Cancer Center, New York               | 9    | 7.8  | 316   | 9.6  | 6   | 35.11             | 1.23              |
| Total of 10 organizations                 |  | 116  | 100  | 3290  |      | 7.6 | 28.8<br>(average) | 1.01<br>(average) |
| Global share                              |  | 561  |      | 12118 |      |     |                   |                   |
| Share of 10 organizations in global Total |  | 20.7 |      | 27.15 |      |     |                   |                   |

Further analysis indicates that Tabriz University of Medical Sciences, Iran, leads institutional contributions with 15 highly cited papers (13.0 percent of the total), accumulating a total of 611 citations and an average of 47.0 citations per paper, which reveals the strong influence of herbal medicine research. Among other organizations, Guangzhou University of Chinese Medicine, China (460), Ministry of Education of the People's Republic of China, China (413), Harvard Medical School, Boston (404), and Memorial Sloan-Kettering Cancer Center, New

York (316) have received the highest citations.

Five organizations have registered citation impact per paper and relative citation index above the average impact of 28.8 and 1.01: Tabriz University of Medical Sciences, Iran (CPP 47.0 and RCI 1.66), Harvard Medical School, Boston (CPP 44.88 and RCI 1.56), Guangzhou University of Chinese Medicine, China (38.33 CPP and 1.36 RCI), Ministry of Education of the People's Republic of China, China (CPP 31.8 and 1.13 RCI), and Memorial Sloan-Kettering Cancer Center, New York (CPP 35.11 and 1.23 RCI).

The three organizations have 9 h-indexes: Shanghai University of Traditional Chinese Medicine and China Academy of Chinese Medical Sciences, China, and Harvard Medical School, Boston, whereas institutions with 8 h-indexes are: Kyung Hee University, South Korea; Tabriz University of Medical Sciences, Iran, and Mashhad University of Medical Sciences, Iran.

#### Most Productive and Impactful countries

Table 6 indicates the country collaboration publications. China is heading the research area in Herbal medicine as therapy for cancer studies,

contributing 174 (33.40 per cent) publications. However, India contributed 98 (18.81 per cent) publications, and the United States has a total of 65 (12.48 per cent) publications. Though China and India have the highest number of research papers, the average citation per paper is significantly low (7.51 and 13.85). Further analysis reveals that the United States, despite collaborating on 65 papers (12.48 per cent), has the highest total citations (2522) and the highest Average Citations per paper (ACP) of 38.80, depicting the global impact of its research contributions.

**Table 6:** Most Productive and Impactful Country/Territory

| Sr. No. | Country/Territory | TP  | %     | Cited | %     | CPP   | H-Index | RCI  |
|---------|-------------------|-----|-------|-------|-------|-------|---------|------|
| 1.      | China             | 174 | 33.40 | 1307  | 13.54 | 7.51  | 31      | 0.41 |
| 2.      | India             | 98  | 18.81 | 1357  | 14.06 | 13.85 | 19      | 0.75 |
| 3.      | United States     | 65  | 12.48 | 2522  | 26.13 | 38.80 | 22      | 2.10 |
| 4.      | Iran              | 57  | 10.94 | 1646  | 17.06 | 28.88 | 21      | 1.55 |
| 5.      | South Korea       | 41  | 7.87  | 618   | 6.40  | 15.07 | 14      | 0.81 |
| 6.      | Australia         | 19  | 3.65  | 372   | 3.85  | 19.58 | 12      | 1.05 |
| 7.      | Taiwan            | 18  | 3.45  | 490   | 5.08  | 27.22 | 12      | 1.47 |
| 8.      | Saudi Arabia      | 17  | 3.26  | 426   | 4.41  | 25.06 | 10      | 1.35 |
| 9.      | Germany           | 17  | 3.26  | 506   | 5.24  | 29.76 | 8       | 1.61 |
| 10.     | Egypt             | 15  | 2.88  | 407   | 4.22  | 27.13 | 8       | 1.46 |
| Total   |                   | 521 | 100   | 9651  |       |       |         |      |

Germany, Iran, Taiwan and Egypt show strikingly high ACP values (29.76, 28.88, 27.22, and 27.13, respectively), implying their research contributions may be fewer but are highly impactful. Saudi

Arabia and Australia also exhibit less collaboration, 25.06 and 19.58 ACP, indicating robust research quality. Further analysis reveals that the registered relative citation index of the United States is 2.10,

which was above the world average of 1. Furthermore, six countries have registered a Relative citation index above the world average of 1: Germany has 1.61, Iran 1.55, Taiwan 1.47, Egypt 1.46, Saudi Arabia 1.35, and Australia 1.05 during the period 2015-2025.

### Documents by Subject Area

Table 7 provides the visual representation of the distribution of documents across different subject areas. This study highlights the dominance of Medicine in this context. Medicine with 343

(38.15 per cent and 37 h-indexes); Pharmacology, Toxicology & Pharmaceutics 226 publications (25.14 per cent and 38 h-indexes) and Biochemistry, Genetics and Molecular Biology with 200 (22.25 per cent and 39 h-indexes) got the maximum number of publications. Whereas, the other subject fields have attained a minimum number of citations (1.11 to 4.12 per cent). Medicine (7420) received the highest citation, followed by Biochemistry, Genetics and Molecular Biology (5875) and Pharmacology, Toxicology and Pharmaceutics (5548).

**Table 7:** Documents by Subject Area

| Sr. No. | Subject Area                                 | TP  | %     | TC    | %     | HI | CPP                | RCI               |
|---------|--|-----|-------|-------|-------|----|--------------------|-------------------|
| 1.      | Medicine                                     | 343 | 38.15 | 7420  | 33.58 | 37 | 21.63              | 0.88              |
| 2.      | Pharmacology, Toxicology and Pharmaceutics   | 226 | 25.14 | 5548  | 21.11 | 38 | 24.55              | 0.84              |
| 3.      | Biochemistry, Genetics and Molecular Biology | 200 | 22.25 | 5875  | 26.58 | 39 | 29.37              | 1.19              |
| 4.      | Chemistry                                    | 37  | 4.12  | 1126  | 5.10  | 14 | 30.43              | 1.24              |
| 5.      | Chemical Engineering                         | 24  | 2.67  | 851   | 3.85  | 12 | 35.46              | 1.44              |
| 6.      | Nursing                                      | 19  | 2.11  | 336   | 1.52  | 12 | 17.68              | 0.72              |
| 7.      | Agricultural and Biological Sciences         | 17  | 1.90  | 249   | 1.13  | 8  | 14.65              | 0.60              |
| 8.      | Immunology and Microbiology                  | 12  | 1.33  | 364   | 1.65  | 7  | 30.33              | 1.24              |
| 9.      | Engineering                                  | 11  | 1.22  | 133   | 0.60  | 4  | 12.10              | 0.50              |
| 10.     | Computer Science                             | 10  | 1.11  | 197   | 0.89  | 6  | 19.70              | 0.80              |
| Total   |  | 899 |       | 22099 |       |    | 23.59<br>(average) | 0.95<br>(average) |

Three subjects have registered above average citation impact per paper (23.59) and relative

citation index (0.95): Chemical Engineering (CPP 35.46, RCI 1.44), Chemistry, Immunology, and Microbiology (CPP 30.43, RCI 1.24 each), and Biochemistry, Genetics, and Molecular Biology (CPP 29.37, RCI 1.19).

### Leading Funding Sponsor

A factorial map of the top ten funding sponsors is presented in Table 8, highlighting the dominance of the sponsoring body in publication. The study

noted that the National Natural Science Foundation of China has funded a total of 69 (44.80 per cent) publications, which received the highest number of citations, 2344 (42.14 per cent) and 22 h-indexes, followed by the National Institutes of Health with 1070 (19.24 per cent) citations on 14 documents (9.10 per cent). Among other funding sponsors, the Fundamental Research Funds for the Central Universities has received 754 citations on 6 documents.

**Table 8:** Documents per year by Funding Sponsor

| Sr. No. | Funding Sponsor   | TP  | %     | TC   | %     | HI | CPP                | RCI               |
|---------|---|-----|-------|------|-------|----|--------------------|-------------------|
| 1.      | National Natural Science Foundation of China            | 69  | 44.80 | 2344 | 42.14 | 22 | 33.97              | 0.94              |
| 2.      | National Institutes of Health                           | 14  | 9.10  | 1070 | 19.24 | 8  | 76.42              | 2.11              |
| 3.      | National Cancer Institute                               | 13  | 8.44  | 402  | 7.23  | 8  | 30.92              | 0.86              |
| 4.      | National Research Foundation of Korea                   | 12  | 7.80  | 217  | 3.90  | 8  | 18.08              | 0.50              |
| 5.      | Ministry of Health and Welfare                          | 11  | 7.14  | 139  | 2.50  | 6  | 12.6               | 0.35              |
| 6.      | Korea Health Industry Development Institute             | 9   | 5.84  | 62   | 1.11  | 4  | 6.89               | 0.19              |
| 7.      | China Postdoctoral Science Foundation                   | 7   | 4.54  | 206  | 3.70  | 5  | 29.43              | 0.81              |
| 8.      | Ministry of Science and Technology, Taiwan              | 7   | 4.54  | 210  | 3.77  | 6  | 30                 | 0.83              |
| 9.      | Fundamental Research Funds for the Central Universities | 6   | 3.90  | 754  | 13.55 | 5  | 125.67             | 3.47              |
| 10.     | Ministry of Education                                   | 6   | 3.90  | 158  | 2.84  | 5  | 26.33              | 0.73              |
| Total   |   | 154 | 100   | 5562 |       |    | 39.03<br>(average) | 1.08<br>(average) |

The h-index of the National Natural Science Foundation of China is 22, whereas other funding

sponsors are included in a range of 5 to 8. Two funding sponsors have registered citation impact

per paper and relative citation index above the average impact of 39.03 and 1.08: The Fundamental Research Funds for the Central Universities (CPP 125.67 and RCI 3.47) and the National Institutes of Health (CPP 76.42 and RCI 2.11).

### Factorial map of the Highly cited Papers

The highly cited paper has the highest citations 732 and document type is Review entitled “Pediatric Gastroesophageal Reflux Clinical Practice Guidelines: Joint Recommendations of the North American Society for Pediatric Gastroenterology, Hepatology, and Nutrition and the European Society for Pediatric

Gastroenterology, Hepatology, and Nutrition” published in the Journal of Pediatric Gastroenterology and Nutrition, volume 66, issue 3 in the year 2018, closely followed by 612 citations on article “Traditional Chinese medicine as a cancer treatment: Modern perspectives of ancient but advanced science” published in Journal Cancer Medicine, volume 8, issue 5 (Table 9). The article “Naturally occurring anti-cancer compounds: Shining from Chinese herbal medicine” ranked 3rd in the highest citations of 413, which was published in the journal Chinese Medicine United Kingdom, volume 14, issue. All the highest cited are Reviews published in journals.

**Table 9:** Highly cited papers

| Sr. No. | Year | Title  | Name of Journal                                     | No. of citations | Volume | Issue |
|---------|------|--|---|------------------|--------|-------|
| 1.      | 2018 | Pediatric Gastroesophageal Reflux Clinical Practice Guidelines: Joint Recommendations of the North American Society for Pediatric Gastroenterology, Hepatology, and Nutrition and the European Society for Pediatric Gastroenterology, Hepatology, and Nutrition ( <b>Review</b> ) | Journal of Pediatric Gastroenterology and Nutrition | 732              | 66     | 3     |
| 2.      | 2019 | Traditional Chinese medicine as a cancer treatment: Modern perspectives of ancient but advanced science ( <b>Review</b> )  | Cancer Medicine                                     | 612              | 8      | 5     |
| 3.      | 2019 | Naturally occurring anti-cancer compounds: Shining from Chinese herbal medicine ( <b>Review</b> )  | Chinese Medicine United Kingdom                     | 461              | 14     | 1     |
| 4.      | 2018 | Application of active targeting nanoparticle delivery system for chemotherapeutic drugs and traditional/herbal medicines in cancer   | International Journal of Nanomedicine               | 361              | 13     | -     |

|     |      |   |  |     |     |   |
|-----|------|---|--|-----|-----|---|
|     |      | therapy: A systematic review <b>(Review)</b>  |  |     |     |   |
| 5.  | 2015 | Recent developments in curcumin and curcumin based polymeric materials for biomedical applications: A review <b>(Review)</b>            | International Journal of Biological Macromolecules | 238 | 81  | - |
| 6.  | 2020 | Positive Role of Chinese Herbal Medicine in Cancer Immune Regulation <b>(Article)</b>   | American Journal of Chinese Medicine               | 214 | 48  | 7 |
| 7.  | 2022 | Naringenin: A potential flavonoid phytochemical for cancer therapy <b>(Review)</b>  | Life Sciences                                      | 212 | 305 |   |
| 8.  | 2019 | Current perspectives in the application of medicinal plants against cancer: Novel therapeutic agents <b>(Review)</b>                    | Anti Cancer Agents in Medicinal Chemistry          | 196 | 19  | 1 |
| 9.  | 2019 | Photodynamic therapy for cancer: Role of natural products <b>(Review)</b>   | Photodiagnosis and Photodynamic Therapy            | 195 | 26  | - |
| 10. | 2018 | Herbal medicine for depression and anxiety: A systematic review with assessment of potential psycho-oncologic relevance <b>(Review)</b> | Phytotherapy Research                              | 181 | 32  | 5 |

### Summary and Conclusion

In conclusion, the worldwide recognition of herbal medicines is affordable, accessible and plays a productive role in preventive and therapeutic healthcare. These breakthroughs have made herbal agents more effective and safer in clinical use. The present study provides a comprehensive analysis of the most influential contributions in this field, accentuating the impact of researchers and institutions in global scientific literature. The study applied scientometric indicators to assess citation patterns, leading authors, key journals, institutional contributions, funding sponsors and most productive and

impactful countries. The scientometric analysis of the SCOPUS dataset pertaining to the use of herbal medicine as a therapy for cancer reveals a vigorous and progressing research perspective. The assessed records chiefly consist of reviews and original research articles, highlighting a dual focus on integrated knowledge and Phytoconstituents. The study was conducted in 74 countries, and the citation impact averaged 17.21 citations per paper during the period 2015 to 2025. The findings indicated that China and India have made notable contributions in the field of herbal medicine research. The journal "Evidence-Based Complementary and Alternative Medicine,

USA” has made a significant contribution with 429 citations on 11 documents. The foremost organisational contribution goes to “Tabriz University of Medical Sciences, Iran”, and the clustering of research topics suggests dominant subjects such as Medicine and Pharmacology, Toxicology and Pharmaceutics. The top ten productive organisations, and together authors contributed 20.7 per cent, 9.0 per cent, 27.5 per cent, and 13.5 per cent global citation share, respectively, during 2015 - 2025.

The low productivity of herbal medicine as a therapy for cancer research during the past 10 years depicts that it is still at a primary level. The collaboration at the national and international levels regarding herbal medicine research is crucial. Herbal medicine can serve as a boon for cancer with fewer side effects and may help to mitigate the cancer disease. It has become imperative to elevate research in the field of herbal medicine.

### Practical implication

A significant insight is provided in the study into the use of herbal medicine as therapy for cancer. The various research studies on the usage of herbal medicine confirm its effectiveness; still, much more is needed to ensure the cure of any form of cancer and effective treatment practices.

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## **Natural Modulators of Cholesterol Metabolism: Bridging Nutrition and Cardiovascular Health**

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### **Abstract**

Cardiovascular diseases (CVDs) represent the leading cause of global mortality, predominantly driven by dyslipidemia and elevated plasma low-density lipoprotein cholesterol (LDL-C). With the growing burden of CVDs, there is urgent need to focus research efforts on identifying effective preventive/therapeutic strategies. Imbalanced cholesterol metabolism reflected by high LDL and reduced HDL promotes atherosclerosis, thus lipid regulation remains key to CVDs prevention. Although statins are widely prescribed for the management of CVDs, concerns regarding their long term side effects have prompted growing interests in nutraceuticals to control dyslipidemia. Nutraceuticals and bioactive compounds such as plant sterols, stanols, phytochemicals like resveratrol, red yeast rice, and spices have gained considerable attention for their ability to modulate lipid metabolism and improve cardiovascular function. The present review aims to shed light on the certain nutraceuticals/dietary bioactive compounds for their potential role normalization of dyslipidemia through alteration of relevant molecular mechanisms. Further, despite promising efficacy, clinical utility of these compounds is constrained by poor solubility, rapid metabolism, and limited bioavailability. Nanocarrier-based delivery systems have enhanced the stability and pharmacokinetics of agents like curcumin, resveratrol, and allicin. Furthermore, combination of nutraceuticals and computationally driven bioactive discovery are advancing personalized approaches to dyslipidemia management. Integrating these natural modulators with lifestyle interventions offers a safe, multi-targeted, and sustainable strategy to mitigate hypercholesterolemia and cardiovascular risk.

**Keywords:** Nutraceuticals, bioavailability, dyslipidemia, lipid-lowering agents

### **1. Introduction**

Cardiovascular diseases (CVDs) including stroke and atherosclerotic cardiovascular disease (ASCVD) are the leading cause of mortality worldwide, with their prevalence expected to rise in the future. The Global Burden Data from 2019 demonstrates that the prevalent cases of total CVDs nearly doubled from 271 million in 1990 to 523 million cases in 2019, and number of deaths steadily increased from 12.1 million in 1990 to 18.6 million in 2019 (Roth et al., 2020). In 2019, nearly 17.9 million people died of CVDs, accounting for 32% of all deaths worldwide and 49.2% of them were due to Ischemic Heart Disease

(IHD) (Makhmudova et al., 2021; Roth et al., 2020). ASCVD was once considered a disease of the industrialized world, but now it spans the globe, and accounts for majority of mortality worldwide (Libby, 2021). Traditional risk factors contributing to CVD include chronic inflammation, hypertension, obesity, diabetes mellitus, and modified lipid metabolism (Joseph et al., 2017). In the beginning of 20<sup>th</sup> century, lipids were found to be the key players involved in the development of atherosclerosis, demonstrating cholesterol being a major component in atherosclerotic plaques. Further investigations

revealed that elevated cholesterol levels mainly low-density lipoprotein (LDL)-cholesterol correlated with an increasing risk of CVDs (KANNEL et al., 1979). Although cholesterol plays an important role in many physiological processes, it has gained a bad reputation in the world of health and nutrition due to its association with cardiovascular diseases (Cerqueira et al., 2016), especially atherosclerosis and ischemic heart disease (Burnett et al., 2020; Schade et al., 2020; Varbo et al., 2013). According to a World Health Organization study in 2008, 40% of the world population is estimated to have cholesterol levels higher than the recommended value of 200 g/ dl (*World Heart Federation, 2022*). Adequate control of cholesterol is important for preventing CVDs. The use of natural compounds for the control of plasma cholesterol levels has recently garnered attention due to their potential to lower plasma cholesterol levels potentially reducing the risk of developing CVDs. This review will appraise the wide use of cholesterol-lowering agents- statins, their associated adverse effects, and the growing interest in natural alternatives, highlighting their mechanism of action and preventive/therapeutic potential in managing dyslipidemia.

## 2. Cholesterol Synthesis and metabolism

Cholesterol is an essential constituent of plasma membranes with nearly 80-90% localized within them and regulates membrane fluidity, reduces membrane permeability, and serves as a precursor for major physiological molecules (Yeagle, 1985). In adults, 500 mg of cholesterol is converted to bile acids every day through nearly 17 enzymes present in the liver (Russell, 2003). Steroid hormones are also synthesized from cholesterol such as glucocorticoids (cortisol, corticosterone), mineralocorticoids (aldosterone) in the adrenal cortex, estrogens (estradiol), progestins (progesterone) and androgens (testosterone,

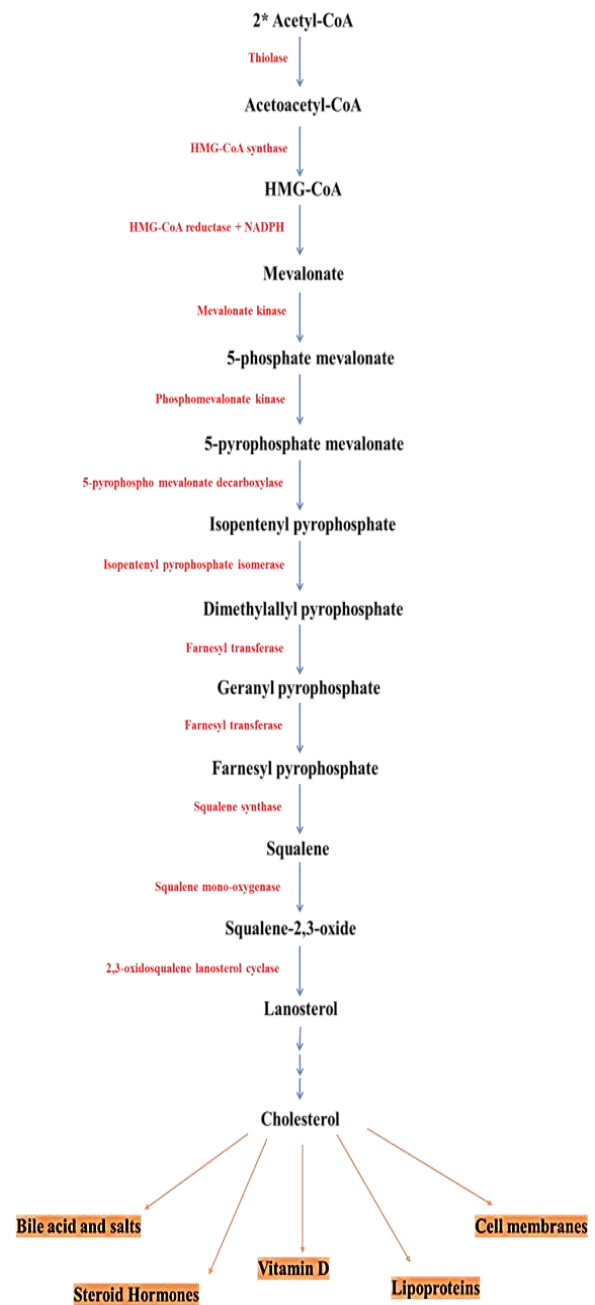
dihydrotestosterone) in the gonads, and calciferols which form the functional forms of Vitamin D in the kidneys (Miller, 2013).

Cellular cholesterol levels are maintained by the interplay between its biosynthesis, its uptake, export and storage (Luo et al., 2020; Nakano et al., 2019). The liver plays a central role in the metabolism of cholesterol where biosynthesis starts from Acetyl CoA involving more than 30 enzymes of the Mevalonate pathway, mostly localized in the Endoplasmic Reticulum, and ultimately produces cholesterol (**Figure 1**) (Cortes et al., 2014; Luo et al., 2020). Two molecules of Acetyl CoA are condensed to form acetoacetyl CoA, followed by addition of another Acetyl CoA molecule to form HMG CoA. This molecule then undergoes reduction to form Mevalonate catalyzed by HMG CoA reductase, which is the rate limiting step of the cholesterol biosynthesis pathway, and a key target of lipid-lowering therapies. Mevalonate is further processed to form two activated isoprene subunits (isopentanyl-5-pyrophosphate and dimethylallyl pyrophosphate) from which, upon a series of successive condensation reactions, squalene is formed. Squalene is a linear compound, which undergoes several reactions leading to production of cyclic compound lanosterol, and ultimately to the production of cholesterol (Cerqueira et al., 2016).

Cholesterol synthesis is efficiently regulated by a chief transcriptional conductor of lipid metabolism, Sterol Regulatory Element Binding Protein (SREBP) (Gelissen and Brown, 2017). Cholesterol is also frequently obtained from the diet in the form of dietary cholesterol, absorbed from the jejunum portion of the intestine via a transporter protein called the Niemann-Pick C1 Like 1 Protein (NPC1L1) (Altmann et al., 2004). In healthy humans normally 50% of the intestinal cholesterol is absorbed, which comprises of dietary cholesterol, biliary cholesterol, and

intestinal cholesterol secretions. Absorption into the enterocytes only takes place when the cholesterol esters are hydrolyzed. Efflux of cholesterol or of plant sterols, stanols back into intestinal lumen takes place due to certain transporters called ATP-binding cassette transporter G5/G8 (ABCG5 and ABCG8) (van der Wulp et al., 2013). Cholesterol once absorbed into enterocytes, travels to the endoplasmic reticulum, where it gets esterified by acyl CoA: cholesterol acyltransferase 2 (ACAT2) and is incorporated into particles called Chylomicrons (CM) along with triglycerides (TGs) and ApoB48 protein to be sent into circulation. Chylomicrons are a class of intestinally derived lipoproteins which transport dietary fats and cholesterol, and other classes of lipoproteins include hepatic-derived Very Low Density Lipoproteins (VLDL), Intermediate Density Lipoproteins (IDL), LDL and intestinally or hepatic-derived High Density Lipoproteins (HDL) (Ginsberg, 1998). VLDL usually transports TGs and cholesterol secreted by the liver, and both Chylomicrons and VLDL are hydrolyzed at the capillary surfaces by enzymes lipoprotein lipases to produce smaller remnant particles, which are believed to be atherogenic. LDL carries nearly three-fourths of the cholesterol in blood, and nearly two-third of it is taken up by cells via LDL receptor-mediated endocytosis (Brown and Goldstein, 1986; Gotto, 1990). HDL, on the other hand, removes excess cholesterol from the circulation or peripheral tissues and transports it back to the liver. Since LDL contributes towards increasing concentration of cholesterol in circulation, it is termed as “Bad Cholesterol” whereas HDL leads to its removal from the circulation, it is commonly called as “Good Cholesterol” (Chen et al., 2008). Dysregulation of LDL uptake is frequently implicated in diseases like hypercholesterolemia, hyperlipidemia and atherosclerotic plaque development. VLDL and elevated triglycerides promote inflammation

whereas HDL exerts antioxidant/anti-inflammatory effects, leading to the attenuation of atherosclerosis progression (Helkin et al., 2016). A study found that every 1mmol/L (38.7mg/dL) reduction in LDL-c is associated with a significant 22% reduced risk in major vascular and coronary events (Ward et al., 2019).



**Figure 1:** Schematic representation of the cholesterol biosynthetic pathway (mevalonate pathway) and its important derivatives.

### 3. Statins-The cornerstone in cholesterol management

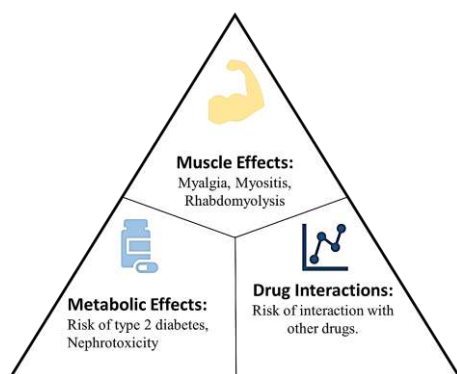
Statins have become the most widely prescribed lipid-lowering drugs administered to patients with elevated serum cholesterol levels and those at high risk of CVDs (Bonetti et al., 2003). Previous studies have confirmed that statins reduce the incidence of CVDs by 23%, making them the first choice of treatment for hyperlipidemia (Hudock et al., 2023; Ray et al., 2016; Yu and Liao, 2022). The discovery of statins dates back to 1976, when mevastatin was isolated from fungi and was seen to have hypocholesterolemic activity (Endo et al., 1976). At the same time, another statin lovastatin (mevinolin) was also discovered from another fungus, which not just demonstrated hypocholesterolemic activity, but also acted by upregulating the expression of LDL receptor, which enhances the uptake of LDL from plasma. In 1987, lovastatin was approved by the US Food and Drug Association (FDA) and became the first commercially available statin. Statins are potent competitive inhibitors of 3-hydroxy-3-methylglutaryl CoA (HMG CoA) reductase, the rate limiting enzyme in cholesterol biosynthesis. The active component in statins, or the pharmacore, is a modified 3,5-dihydroxyglutaric acid moiety, which shows structural resemblance to the enzyme's endogenous substrate HMG CoA, and hence upon binding to its active site, inhibits its activity (Ward et al., 2019). Some statins such as lovastatin, pravastatin, simvastatin are fungal derivatives while others like atorvastatin, cerivastatin, fluvastatin, pitavastatin and rosuvastatin are fully synthetic statins. Studies have shown that statin therapy causes a 20%-50% reduction in LDL-c levels and, a 10%-20% reduction in triglycerides, potentially increasing serum HDL levels by 5%-10% (Barter et al., 2010; Odden et al., 2015; Taylor et al., 2013).

Due to cardiovascular benefits, the statins became

the most prescribed classes of drugs but certain commonly associated risks and adverse effects that statins may cause cannot be overlooked (**Figure 2**). Statin-induced myalgia is a very frequent phenomenon encountered in patients, and in many cases, it may lead to statin myopathy and acute rhabdomyolysis (Sirtori, 2014). In a study carried out on 45 patients, most developed myopathy, although statin-associated myopathy experienced full resolution of muscle pain upon the attenuation of statin therapy. Nearly 13% of patients required hospitalization for rhabdomyolysis, and half of them experienced renal dysfunction (Hansen et al., 2005). The potent statin cerivastatin was withdrawn from the market due to the occurrence of fatal rhabdomyolysis cases. It has been proposed that risk of myopathy is greater with lipophilic statins than hydrophilic statins because of their ability to enter muscle cells and alter membrane structure (Pierno et al., 2006).

Multiple studies have also found out the correlation between statin therapy and increased incidences of Type 2 Diabetes mellitus (T2DM). In 2012, United States Safety and Drug Administration released changes in statin safety label and stated that statins increase glycosylated hemoglobin A1c (HbA1c) and fasting glucose concentrations (Laakso and Fernandes Silva, 2023). One of the first studies linking statins with the risk of T2D was the WOSCOPS trial, in which a total of 5974 participants did not have diabetes at baseline, and 139 of them developed T2D during the study (Freeman et al., 2001). In another study, atorvastatin therapy, especially in higher dose was found to be associated with glucose intolerance and caused progression towards diabetes in pre-diabetic patients (Parida, 2017). JUPITER trial, performed on 17,802 healthy participants also concluded that rosuvastatin successfully reduced the incidences of major cardiovascular events by 44%, but also caused 26% times higher incidences of physician-reported diabetes as compared to

placebo group (Ridker et al., 2008). Since patients with hyperlipidemia also present other medical issues including hypertension, diabetes, and coronary artery disease, statins are frequently administered in combination with other drugs. This increases the risk of several drugs interfering with the metabolism of statins and potentially increasing the adverse events related to statins (Bottorff, 2006). Nearly 60% of statins-related rhabdomyolysis cases are related to drug-drug interactions (Kashani et al., 2006). While statins remain the major pharmacological management for hypercholesterolemia, the adverse side effects associated with it have encouraged the exploration of alternative strategies. Among these, dietary interventions have emerged as a major approach to modulate lipid metabolism and reduce the risk of CVDs.



**Figure 2:** Adverse effects and risks associated with statins

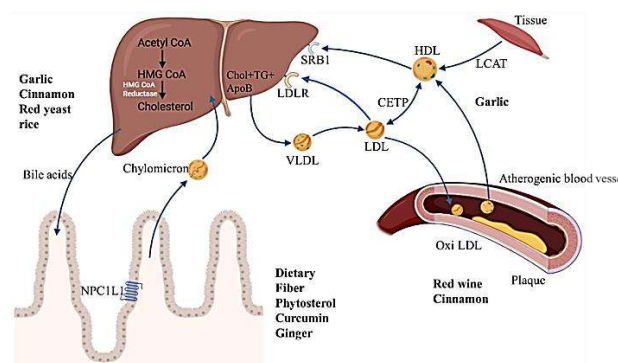
#### 4. Dietary interventions for lipid control

Diet is the major factor which can influence the health of individuals, and choosing the right components in diet can delay or even avoid the occurrence of several diseases. Diet plays a crucial role in determining the lipid profile of any individual, which is a major risk factor for CVD (Ma et al., 2012). A dietary supplement is defined as any product which augments the nutritional

value of everyday food intake, including vitamins, minerals, herbs or amino acids (Grant et al., 2023). In the US, between 2007-2008 and 2017-2018, dietary supplement use increased from 48.6% to 56.1% and the sale of dietary supplements accounted for an estimated 50 billion dollars in 2020 (Grant et al., 2023). These dietary interventions can be broadly divided into three categories based on their origin:

1. Plant-based nutraceuticals which include phytosterols, and dietary fibers
2. Spices-derived phytochemicals including curcumin, cinnamon, garlic, and ginger
3. Fermented nutraceuticals which include red wine, and red yeast rice

The natural dietary interventions exhibiting a range of cholesterol lowering effects including inhibition of intestinal cholesterol absorption, decreased hepatic synthesis, and enhanced bile acid excretion have been summarized in **Figure 3**. These naturally occurring bioactive components, ranging from plant derived phytoconstituents to fermented compounds are found in commonly consumed foods and were selected based on comprehensive experimental and clinical evidences regarding their lipid lowering activities and safety.



**Figure 3:** Overview of lipoprotein metabolism and specific mechanisms targeted via nutraceutical modulation. The figure depicts lipid transport and cholesterol regulation involving chylomicrons,

VLDL, LDL and HDL. Cholesterol uptake and efflux occur via LDLR and SRB1, while LCAT and CETP mediate lipid exchange between lipoproteins. Accumulation of oxidized LDL in blood vessels leads to plaque formation and atherogenesis. Cholesterol lowering agents such as garlic, cinnamon, and red yeast rice block cholesterol synthesis via inhibition of enzyme HMG CoA reductase in the liver, while dietary fibers, phytosterols, curcumin and ginger act via inhibiting absorption of dietary cholesterol in the small intestines. Anti-atherogenic effects are seen in the case of red wine and cinnamon, which prevent platelet aggregation and lipid peroxidation in the blood vessels, respectively, while garlic downregulates CETP, leading to lower levels of LDL-c and enhanced levels of HDL-c. ApoB, apolipoprotein B; CETP, cholesteryl ester transfer protein; HDL, high density lipoproteins; LCAT, lecithin cholesterol acyl transferase; LDL, low density lipoproteins; LDLR, low density lipoprotein receptor; NPC1L1, Niemann-pick C1 like 1 receptor; oxi-LDL, oxidative LDL; SRB1, scavenger receptor B1; TG, Triglycerides; VLDL, very low-density lipoproteins

#### **4.1 Plant-Based nutraceuticals**

##### **4.1.1 Phytosterols**

Phytosterols play important structural roles in plant cells, and are constituents of the cell membranes, stabilizing the phospholipid bilayer and mostly found in vegetable oils, legumes, seeds, nuts and cereals (Ge et al., 2024). These food sources contribute nearly 50-80% of daily sterol intake, while fruits adding further 12% more to it (Klingberg et al., 2008). Plant sterols have been widely used as functional ingredients in foods, medicines, cosmetic products and nutraceuticals. The major role played by phytosterols is during the intestinal absorption process, which can be described as a triphasic process. In the first phase, there is incorporation of

dietary cholesterol and other phytosterols into mixed micelles in the intestinal lumen. The second phase is characterized by uptake of these micelles into the enterocytes via NPC1L1 receptors, and the third phase comprises of the esterification and further modification of cholesterol to form transportable molecules called chylomicrons. Bulks of plant sterols/stanols are pumped back into gut lumen via ABCG5/ABCG8 transporters, to minimize their entry into the circulation. Hence, presence of phytosterols in the diet causes competition for absorption of cholesterol, thereby causing inhibition or reduction in its absorption (Gylling et al., 2014).

Plant stanols/sterols also cause enhanced transcription of mRNA encoding LDL receptors, which cause elevation in expression of LDL receptors, and therefore a decrease in circulating LDL cholesterol. As phytosterols cause decrease in cholesterol intake, it causes a boost in the endogenous cholesterol synthesis, which is usually overcome by the use of statins, which lower the endogenous cholesterol production, hence forming an effective drug combination for lowering cholesterol levels, particularly total cholesterol and LDL cholesterol (Blair et al., 2000; Plat and Mensink, 2005). In fact, adding sterols/stanols to statin medication is much more effective than doubling the statin dose (Katan et al., 2003).

Phytosterols also lower LDL levels by inhibiting LDL apolipoprotein B production. Ample amount of evidence indicates that consuming 2g/day of sterols/stanols lower LDL levels by 10%, and many epidemiological data and trials indicate that long term use of sterols/stanols can lower risk of CHD (coronary heart disease) by 12% to 20% in the first 5 years, and by 20% over a lifetime (Katan et al., 2003). A pooled analysis of 12 randomized controlled trials also showed that phytosterols intake of around 2g/day in hypercholesterolemic patients caused a 6% reduction in the serum

triglycerides (TG) levels (Demonty et al., 2013). Phytosterols are therefore a good alternative for cholesterol lowering, and can be used with statin medications as well, leading to additive effects.

#### 4.1.2 Dietary Fibers

Fibers are complex plant-based compounds that are usually resistant to human digestive tract enzymes, and therefore, are not absorbed in the body. They can be classified into two classes, namely insoluble fibers, including lignin, cellulose, hemicellulose, and the soluble fibers, including gums, mucilages and pectins. Consumption of whole grains, wheat, bran, nuts, and seeds, as well as some fruits and vegetables provides insoluble fibers, while soluble fibers are mainly found in fruits including berries, bananas, apples and pears, and vegetables like carrots, broccoli, onions, and artichokes, as well as legumes, oats and barley (Chang and Koegel, 2017). The soluble dietary fibers includes  $\beta$ -glucans, agar, pectin, gums which are usually formed of polysaccharides formed via  $\beta$ -1,3-linked and  $\beta$ -1,4-linked glucose units and their side chains comprising of xylose, mannose, galactose or uronic acid residues (Nie and Luo, 2021). The soluble fibers, or hydrosoluble fibers form an unstirred water layer on the intestinal wall and delay sugar and fat absorption, while the insoluble fibers help in increasing the volume of the stool (Nie and Luo, 2021). A meta-analysis study conducted in patients with CVD and hypertension uncovered that increasing soluble dietary fiber intake reduced total plasma and LDL concentrations by 0.42 and 0.47mmol/L respectively and also assisted in lowering the systolic and diastolic blood pressure in individuals (Reynolds et al., 2022). Some mechanisms believed to be responsible for cholesterol lowering effects of viscous soluble fibers are (i) inhibition of intestinal bile acid reabsorption enhancing its

excretion and hence, stimulates hepatic bile acid synthesis from cholesterol, (ii) reduction of plasma insulin levels by delaying carbohydrate absorption which inhibits hepatic HMG CoA reductase and (iii) production of short chain fatty acids via fermentation caused by colonic microbiota, which inhibits HMG CoA reductase activity and suppresses NPC1L1 receptor expression in the intestine (Ge et al., 2024). The FDA recommends incorporation of 3g/day of  $\beta$ -glucans or 7g/day of soluble dietary fibers from psyllium seed husks to low cholesterol, low saturated fat diets to help in reduction of total cholesterol LDL-c ("Food Labeling," 2008; Gunness and John Gidley, 2010). The daily value recommended by FDA for dietary fiber intake is 28g (Program, 2024).

#### 4.2 Spices derived phytochemicals

Traditionally, spices have been used worldwide for a long time for culinary or medicinal purposes, and consumption of spicy food has been inversely related to total mortality, and reduced deaths due to ischemic heart diseases. A large cohort study indicated that people who consumed spicy foods almost every day had a 14% lower risk of death as compared to people who consumed spicy food only once or less per week (Lv et al., 2015). Several widely consumed spices, including turmeric, cinnamon, garlic, ginger, and pepper, are a rich source of bioactive molecules that possess a diverse range of health benefits. Growing evidences reveal that spices and herbs exhibit promising anti-oxidant, anti-inflammatory, anti-tumorigenic properties and, hypocholesterolemic activity contributing to improvement in lipid profiles (Jiang, 2019). Some of these are discussed briefly below.

##### 4.2.1 Turmeric derived curcumin

Curcumin is a polyphenol derived from the rhizome of turmeric (*Curcuma longa*), and is frequently used as food coloring agent and as dietary spice (Zingg et al., 2013). Curcumin and its

derivatives display very significant hypocholesterolemic effect in hypercholesteremic rats, and reduce LDL-c and VLDL in plasma, as well as reduced total cholesterol level in liver (Chattopadhyay et al., 2004). The mechanism by which curcumin can decrease the LDL-c levels is mainly through the reduction in cholesterol absorption. Feng et al. (2017) showed that curcumin affects the intestinal cholesterol absorption in hamsters by downregulating the intestinal cholesterol transporter NPC1L1 by inhibiting the expression of SREBP2 transcription factor (Feng et al., 2017). ATP-binding cassette transporter A1 (ABCA1) plays a crucial role in cholesterol homeostasis by transferring intracellular cholesterol to lipoprotein deficient apolipoprotein A1 (ApoA-I) proteins for nascent HDL formation and fecal excretion (Chen et al., 2022). Curcumin has also shown to upregulate ABCA1 expression in THP-1 macrophage and ApoE<sup>-/-</sup> mice thus promoting reverse cholesterol efflux (Tan et al., 2021). Furthermore, curcumin downregulates or inhibits fatty acid synthase activity, and significantly elevates HDL-C levels in plasma, thereby improving lipid profile and reducing CVD risk (Jang et al., 2008). A randomized double blind placebo-controlled clinical trial demonstrated that daily consumption of 1500mg/day curcumin significantly reduced TGs, LDL-c, and TC but did not affect HDL-c levels (Saadati et al., 2019). A meta-analysis on effect of curcumin supplementation on lipid profile also revealed promising results as curcumin improved serum LDL-c, TC, TGs, and HDL-c levels (Dehzad et al., 2023).

Apart from the beneficial effect on lipid profile, it also offers anti-inflammatory effects through the inhibition of NF- $\kappa$ B activation, accompanied by anti-oxidant, anti-cancer, cytoprotective and anti-depressant effects (Chattopadhyay et al., 2004; Panahi et al., 2018). Incorporation of turmeric in diet is therefore highly recommended due to

presence of curcumin, a bioactive component with several beneficial health potential. Besides various biological actions of curcumin in several diseases, the bioavailability, low solubility, and rapid metabolism of curcumin poses a major concern for its pharmacological use (Racz et al., 2022).

#### 4.2.2 Cinnamon

Cinnamon is another widely used spice, which is used as herbal medicine, as a flavoring agent, and also for fragrance. The leaves and majorly bark of the cinnamon trees are used for consumption (Mohammadabadi and Jain, 2024). There are more than 250 species of the genus *Cinnamomum* but the main ones from which cinnamon is commercially extracted are *Cinnamomum verum* (Ceylon Cinnamon), *Cinnamomum burmanii* (Korintje Cinnamon), *Cinnamomum cassia* (Saigon Cinnamon), and *Cinnamomum loureirii* (Royal Cinnamon) (Das et al., 2022). The main constituents of cinnamon are cinnamaldehyde and trans-cinnamaldehyde present in its oils, and the major bioactive compounds present in cinnamon have been reported to be flavonoids like catechins, procyanidins, and many phenolic compounds like protocatechuic acid, quercetin, p-coumaric acid, p-hydroxybenzoic acid, rosmarinic acid, caffeic acid and ferulic acid to name a few (Das et al., 2022; Vallverdú-Queralt et al., 2014).

Cinnamon acts via various proposed mechanisms and results in lowering of blood lipid levels, along with numerous other benefits like anti-inflammatory, anti-oxidative, anti-diabetic, and antihypertensive activities (Mohammadabadi and Jain, 2024). Certain bioactive compounds such as cinnamate display significant hypocholesterolemic activity as they reduce hepatic cholesterol concentrations and triglycerides concentrations, which is achieved by their inhibitory effect caused on hepatic HMG CoA reductase enzyme (Lee et al., 2004). Certain polyphenols in cinnamon also reduce oxidative

stress by inhibiting 5-lipoxygenase enzyme, thereby causing decreased incidences of lipid peroxidation (Mollazadeh and Hosseinzadeh, 2016; Rahman et al., 2013). Another study demonstrated that cinnamon extract significantly increases insulin sensitivity, reduces serum, and hepatic lipids, and improves hyperglycemia and hyperlipidemia possibly by regulating the PPAR-mediated glucose and lipid metabolism in mice. (Kim and Choung, 2010).

#### 4.2.3 Garlic

Garlic is an extensively used flavoring agent used worldwide characterized by high contents of flavonoids and organosulfur compounds including allicin, alliin, S-allylcysteine, or S-allyl mercaptocysteine. Research suggests that garlic is associated with reduction in blood cholesterol, triglycerides, liver lipids, primarily seen in LDL-c and VLDL-c fractions (Chi, 1982; Srinivasan, 2013). Water soluble garlic extracts were also seen to reduce the activity of hepatic HMG CoA reductase and thereby decrease cholesterol biosynthesis and blood cholesterol levels (Gebhardt, 1991; Srinivasan, 2013). Allicin is a major component of garlic known to inhibit HMG-CoA reductase, and acetyl CoA reductase (Borlinghaus et al., 2014). Allicin which is naturally not present in raw garlic is only produced upon cell rupture which triggers an enzyme alliinase to convert alliin into allicin.

Several clinical studies and meta-analysis reveal the potential of different garlic extracts in dyslipidemia. A meta-analysis of randomized controlled trials show that different preparations raw garlic/aged garlic extract/garlic powder tablets were related to lowering of TC, LDL, and improvement in HDL levels (Zhao et al., 2024). Another study observed that consumption of 100mg/kg of crushed garlic twice a day for four weeks proved beneficial against HDL and TG in metabolic syndrome patients (Choudhary et al.,

2018). In a recent study diallyl disulfide (DADS) supplementation ameliorated the dysfunctional lipid metabolism in western diet fed ApoE deficient mice. Decreased plasma levels of TC is linked with suppression of hepatic ER stress suggesting that DADS may be useful in diet-induced hypercholesterolemia (Kim and Kim, 2023). However, the role of garlic in hypercholesterolemia is controversial as some contrasting results have been observed in some studies where no significant difference has been seen on lipid levels (Li et al., 2023). Despite its controversial role, several mechanisms by which garlic is beneficial have been proposed including (1) inhibition of cholesterologenic and lipogenic enzymes such as malic enzyme, HMG-CoA reductase, fatty acid synthase (FAS) (2) negative regulation of genes involved in cholesterol synthesis such as NPC1L1, cholesteryl ester transfer protein (CETP), (3) increased excretion of acidic and neutral steroids into bile (Sobenin et al., 2019).

#### 4.2.4 Ginger

Ginger, another widely used medicinal and culinary agent, has been used in various ailments including cold, headache, nausea, diarrhea, and arthritis possesses due to its several beneficial properties. Ginger comprises of volatile compounds including sesquiterpenes, and monoterpenes, and non-volatile compounds include biologically major active constituents such as gingerol, shogaols, paradols, and zingerone (Kiyama, 2020). The presence of these biologically active constituents in ginger contributes to its beneficial effects against several diseases including diabetes, metabolic syndrome, lipid metabolism, and inflammation. Studies have reported diminished serum and liver cholesterol levels and increased fecal cholesterol upon consumption of ginger (El Gayar et al., 2019) (de las Heras et al., 2017).

Several *in vivo* studies have reported multiple mechanisms for reducing lipid levels include (1) downregulation of NPC1L1, ACAT2, MTP genes in small intestine altering cholesterol absorption, (2) upregulating LDL receptor (responsible for removal of LDL-c from circulation), and downregulation of HMG-CoA (3) increasing HDL-c synthesis by upregulating ApoA1 (major structural protein of HDL particles), ABCA1, and lecithin:cholesterol acyltransferase (LCAT) (Oh et al., 2017) (Li et al., 2018) (Lei et al., 2014). Apart from the beneficial effects of gingerols and shagaols (major bioactive constituents), ginger oils have also been reported to modulate lipid profile by altering the activities of genes involved in cholesterol homeostasis mainly HMG-CoA-R, SREBP1, and FAS (Lai et al., 2016).

A meta-analysis of ginger supplementation on lipid profile in non-alcoholic fatty liver disease (NAFLD) indicated significant reduction in serum LDL, TC, TG and increase in serum HDL suggesting hepatoprotective potential of ginger (Samadi et al., 2022). Contrastingly, a clinical trial in NAFLD patients who were given 1500mg ginger/day for 12 weeks could not cause significant changes in serum HDL and TG levels (Rafie et al., 2020). Thus, the effect of garlic supplementation for hypercholesterolemia in humans remains controversial potentially due to variations in ginger types and doses, study populations, and geographical factors.

Asafetida, onion, red pepper, fenugreek, are some more culinary agents and food ingredients which confer beneficial effects like cholesterol lowering, anti-oxidant activity and many more, and may be incorporated in diet for achieving a better lipid profile (Srinivasan, 2013).

### **4.3 Fermented nutraceuticals**

#### **4.3.1 Red Wine and the French Paradox**

In most countries, high intake of saturated fats and

dairy fats directly correlates with increased risk as well as mortality from coronary heart disease (CHD), however, in France the situation seems to be contradictory, where there are lower incidences of CHD and myocardial infarction, despite the French people having a high saturated fat and cholesterol rich diet. The mortality rate from CHD is much lower in France as compared to the other industrialized countries. This paradoxical situation is termed as the “French Paradox” (Renaud and Lorgeril, 1992). The French population’s routine consumption of red wine along with meals appears to be the best explanation of this paradox, and moderate doses of 20-30g per day prove to be most effective (Davies et al., 2017; Renaud and Lorgeril, 1992). Red wine contains good amount of flavonols such as quercetin, catechin, epicatechin, proanthocyanidins, anthocyanins, phenolic acids like gallic acid, caffeic acid, p-coumaric acid and the stilbene resveratrol (Catalgol et al., 2012). Resveratrol (trans-3,4',5,-trihydroxystilbene) is a natural phenol and also a phytoalexin produced naturally by nearly 72 plant species such as grapevines, legumes and pines (Catalgol et al., 2012; Soleas et al., 1997). This particular polyphenol exerts a plethora of beneficial effects, and its various biological activities are associated with its structural determinants like number and position of hydroxyl groups, intramolecular hydrogen bonding, and presence of double bond or stereoisomers (Ovesná and Horváthová-Kozics, 2005). Resveratrol has the ability to bind to intracellular and many extracellular receptors or molecules, triggering various signaling pathways in cells via its effect on the extracellular receptors or directly inside the nucleus (Gambini et al., 2015).

In the year 2000, various biological effects of resveratrol such as inhibition of lipid peroxidation and anti-oxidant activity, inhibition of platelet aggregation, anti-inflammatory activity, vasorelaxing activity, anti-cancer activity and

modulation of lipid metabolism were enlisted (Frémont, 2000). Trans-resveratrol chelates copper ions, hence reducing copper-catalyzed LDL-oxidation, which helps in reducing atherosclerotic risk. Another study validating the anti-atherogenic property of resveratrol displayed that platelet aggregation, crucial for initiating atherosclerotic lesions was also inhibited by the compound, which happens via the inhibition of  $\text{Ca}^{2+}$  influx into platelets, thereby causing inability of platelets to aggregate and develop lesions (Wang et al., 2002). It must be noted that the beneficial effects as mentioned, have been attributed to the presence of resveratrol and other polyphenols, and that alcohol does not contribute to any of these beneficial effects.

Red yeast rice (RYR), one of the most effective nutraceuticals in lowering cholesterol levels, is produced by the fermentation of rice (*Oryza sativa*) by yeast (usually *Monascus purpureus*). It results in red coloration of the rice due to pigments, produced upon fermentation (Cicero et al., 2021). It has been used in China for centuries as a food coloring agent as well as flavor enhancer. The European Cardiology Society and European Atherosclerosis Society guidelines, since 2011, have recommended RYR for the effective management of mild hypercholesterolemia in patients who do not qualify for the use of statins (Mach et al., 2019). RYR has major constituents like sugars (25% to 73%, mainly starch), proteins (14% to 31%), water (2% to 7%), fatty acids (1% to 5%) and certain pigments, sterols or isoflavones (Cicero et al., 2021). The major principal active components in red yeast rice are monacolins, particularly monacolin K subtype. It is present in two forms which are the lactone (inactive) and hydroxyl acid (active) form based on the pH. The lactone form of monacolin K is structurally similar to lovastatin, and hence, is a reversible inhibitor of HMG CoA reductase (Cicero et al., 2023, 2021).

A randomized placebo controlled study demonstrated that patients receiving RYR experienced a significant reduction of nearly 23% in the LDL-C levels, whereas a reduction of 15.5% in the TC after 16 weeks of treatment (Bogsrud et al., 2010). In 2011, a Scientific Opinion from European Food Safety Authority (EFSA) panel on Dietetic Products, Nutrition and Allergies also concluded that consumption of 10mg of monacolin K from RYR is associated with maintenance of normal blood LDL-C concentrations, and advised its consumption daily in order to obtain the desired effect (EFSA Panel on Dietetic Products, Nutrition and Allergies (NDA), 2011). In several trials, the reduction was seen primarily in the LDL-C, TC and the triglyceride concentrations and the effect was very similar to that produced by statin treatment such as pravastatin or lovastatin (Banach et al., 2019; Cicero et al., 2005; Heinz et al., 2016).

Several new cholesterol lowering agents still demand further clinical investigation and pharmacological analysis. Along with this, many other strategies are under continuous exploration such as combining different supplements, enhancing the pharmacodynamic properties of existing ones, and many more, which have been briefly discussed in the next section.

## 5. Future Perspectives

### 5.1 Bioavailability enhancement

The cholesterol lowering agents discussed cause significant improvement in lipid profiles and help in lowering the cholesterol levels, but there is a major challenge of pharmacodynamic inefficiency which needs to be addressed in many cases. Curcumin, as discussed earlier, is a great bioactive component of turmeric which confers a wide range of physiological benefits. But its utility is limited due to its poor water solubility, low absorption in the GI tract, poor aqueous dispersion in the body environment at neutral or acidic pH, rapid metabolism to reduced products and their

glucuronide or sulfate conjugates, and thereby quick elimination from the body (Flora et al., 2013). A study showed that administration of curcumin at a dose of 1g/kg b.wt. in rats caused 75% elimination through feces and a negligible amount seen in urine, and poor absorption in the gut (Wahlström and Blennow, 1978). Resveratrol is chemically unstable and poorly soluble in water (Salla et al., 2024). It shows unusually high absorption (nearly 70%), but also gets rapidly metabolized in the liver to its sulfate conjugates and glucuronide conjugates, thereby showing reduced bioavailability (Walle et al., 2004). Such problems of poor pharmacodynamic properties are tackled using nanotherapeutics, where drugs are administered with nano formulations to improve the pharmacokinetic properties, such as better drug penetration into tissues, enhanced bioavailability or sustained and controlled release/delivery of the drug. Curcumin is conjugated with high affinity carriers like PLGA, HAS, glycerol monooleate, polycaprolactone or galactomannans, which enhances its bioavailability by increasing gut permeation, elevating plasma half-life, and preventing quick degradation (Laurindo et al., 2023). Allicin, a bioactive compound of garlic, also exhibits low water solubility and stability, which significantly limits its bio efficacy. Many novel delivery systems- nanoparticles, gels, nanoliposomes have been developed which enhance its solubility, stability, encapsulation efficiency and high retention in target site efficiently regulating dyslipidemia (Bhattacharya et al., 2022; Fan et al., 2023; Olad et al., 2020). Similarly, phytosterols whose absorption rate is 5% may be chemically modified by esterification or physical modification by microencapsulation to enhance their bioavailability (Li et al., 2022).

## 5.2 Combination Therapy

Numerous patients on statin therapy are unable to

meet their lowered LDL cholesterol level goals as specified by the National Cholesterol Education Program (NCEP); hence another approach of combination therapy is brought to use. Patients are supplemented with nutraceuticals like plant sterols/stanols in addition to the statin therapy, which further helps in reducing the cholesterol levels with reduced side effects. A meta-analysis of 8 randomized controlled trials in which sterols/stanols at doses of 1.7-6g/day were given in addition to statin therapy, caused a greater and more significant lowering effect on both total cholesterol levels and LDL cholesterol levels in hypercholesterolemic patients (Scholle et al., 2009).

A combination of nutraceuticals, rather than monotherapy, appears to be a better approach towards lipid lowering treatment as different bioactive compounds may confer different lipid lowering mechanisms, leading to an additive or even a synergistic effect (Protic et al., 2021). A 3 week, randomized, double blind study was conducted in which 60 individuals were given (n=3) LCPUFA (Long chain polyunsaturated fatty acids) in combination with phytosterols, and a synergistic reduction in total and LDL-c by 13.3% and 12.5% was seen along with complementary effects on triglycerides and HDL-c (Micallef and Garg, 2008). Further, daily consumption of dietary supplement consisting of RYR, sugarcane derived policosanols, and artichoke leaf extracts exhibited better efficacy in managing cholesterol compared to individual therapy (Ogier et al., 2013). Such combination therapies may prove to be extremely beneficial for an effective management of hypercholesterolemia.

**Table 1** summarizes the various nutraceuticals with their mechanism of action.

| Nutraceuticals                | Active Compounds                               | Mechanism of Action  | Effect on lipid profile     |
|-------------------------------|--|--|-----------------------------|
| <b>Phytosterols</b>           | $\beta$ -sitosterol, Campesterol, Stigmasterol | Compete with cholesterol in micelles, limit absorption                               | ↓ LDL, ↓ Total-C            |
| <b>Garlic</b>                 | Allicin, S-allyl cysteine                      | Modulates lipid metabolism, natural HMG-CoA reductase inhibition, and antioxidant    | ↓ LDL, ↓ TG, ↑ HDL (small)  |
| <b>Curcumin</b>               | Curcumin                                       | Modulates lipid metabolism, natural HMG-CoA reductase inhibition, and antioxidant    | ↓ LDL, ↓ TG, ↑ HDL          |
| <b>Ginger</b>                 | Gingerols, shogaols                            | Suppresses cholesterol absorption and synthesis, antioxidant & anti-inflammatory     | ↓ LDL, ↓ TG, ↑ HDL          |
| <b>Cinnamon (Turmeric)</b>    | Cinnamaldehyde, polyphenols                    | Mild HMG-CoA reductase inhibition, antioxidant & anti-inflammatory                   | ↓ LDL, ↓ TG (slight), ↑ HDL |
| <b>Dietary Fibers</b>         | $\beta$ -glucan, soluble/insoluble fibres      | Soluble: ↓absorption (unstirred water layer); Insoluble: ↑bile acid/sterol excretion | ↓ LDL, ↓ Total-C            |
| <b>Resveratrol (Red Wine)</b> | Resveratrol, polyphenols                       | Inhibits LDL oxidation, ↓platelet aggregation, and is anti-atherogenic               | ↑ HDL, ↓ LDL oxidation      |
| <b>Red Yeast Rice</b>         | Monacolin K                                    | Inhibits HMG-CoA reductase → ↓cholesterol synthesis                                  | ↓ LDL, ↓ TG (mild), ↑ HDL   |

### 5.3 Computational Bioactive Discovery and Personalized Nutrition

Many developers incorporate bioinformatics and drug discovery approaches in order to identify new nutritional supplements. Researchers first identify various molecular targets involved in cholesterol metabolism (such as enzymes like HMG CoA reductase, ACAT, or transporters like NPC1L1) and then screen libraries of natural compounds *in silico* to find compounds which readily interact with these targets. These predictions are then tested in the lab and later in animal or human studies. This strategy has been used for many discoveries such as specific phenolics, which

block intestinal cholesterol transporter NPC1L1 or certain natural terpenes which upregulate LDL receptors in the liver (Jacobo-Velázquez, 2025). This is still an emerging field, but many discoveries and early successes suggest integrating nutritional science with computational chemistry, laying the foundation for precision functional food design.

Precision functional food or personalized nutrition is based on the principle that different individuals respond differently to same dietary interventions, particularly due to genetic differences, gut microbiome variability or other factors, and one kind of functional food may perform nicely in an

individual but may underperform in other individuals (Jacobo-Velázquez, 2025). Hence, a futuristic approach would be to first identify various genetic markers in individuals to predict their response and acquire their unique genetic profile, and then recommending a specific functional food to them. This would greatly enhance the effectiveness and efficiency of nutritional supplement(s).

## 6 Conclusion

Cardiovascular diseases (CVDs) associated dyslipidemia is characterized by elevated TC, LDL-C and TGs. Hypercholesterolemic patients are commonly prescribed statin therapy, a well-established lipid-lowering drug but statins are associated with several side effects that remain comparatively under-reported. Moreover, many individuals with hypercholesterolemia do not fall into the high-risk category that necessitates statin therapy, and some patients are reluctant to initiate long-term pharmacological treatment. In this context, nutraceuticals have gained considerable attention. Dietary fibers, fermented nutraceuticals and phytochemicals found in turmeric/ginger/garlic/cinnamon have demonstrated promising lipid-lowering potential, particularly among patients with mild hypercholesterolemia. However, their clinical effectiveness is often limited by poor bioavailability, a challenge now being addressed through nanotechnology-based delivery systems. Additionally, combining multiple lipid-lowering agents is emerging as a strategy to achieve additive or synergistic therapeutic benefits. Taken together, in this era of increasing CVD risk, incorporating natural phytochemicals into the daily diet, along with appropriate lifestyle modifications, may support the maintenance of a healthy lipid profile and promote overall well-being.

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# **IOT-ENABLED INFRASTRUCTURE FOR SUSTAINABLE URBAN DEVELOPMENT OF SMART CITIES:**

## **A CITIZEN-CENTRIC APPROACH**

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### **Abstract**

Internet of Things (IoT) technologies are revolutionizing urban infrastructure by interconnecting sensors and systems for real-time monitoring and control. By aggregating data from devices across a city, IoT enables more efficient and sustainable management of resources, improving mobility, energy use, waste disposal, and environmental health. For example, integrating IoT into traffic control systems can significantly reduce congestion and vehicle emissions through adaptive signal timing. Similarly, smart streetlights with motion and environmental sensors cut energy consumption by roughly 30–50% compared to legacy systems. IoT-enabled waste bins and networks optimize collection routes, lowering operational costs and carbon output, while distributed air and water sensors provide city officials with timely environmental risk data. To fully realize these benefits, cities must shift from top-down “technocratic” designs to citizen-centric frameworks. Engaging residents through participatory platforms such as Barcelona’s Decidim ensures that IoT projects address local needs and equity. Emerging technologies like 5G, edge computing, AI, blockchain, SSI can support the vision, but also raise concerns about privacy, interoperability, and the digital divide. Citizen-Centric Standardization Protocol (CCSP) has been proposed during present investigation that embeds co-creation, ethical AI, data sovereignty, and adaptive feedback into smart city design. By standardizing modular IoT platforms and governance around human values, CCSP aims to guide policymakers and practitioners in deploying inclusive, resilient smart city strategies that serve the collective good.

**Keywords:** Smart Cities, Internet of Things (IoT), Citizen-Centric Design.

### **Introduction**

Rapid urbanization and climate pressures have made efficient resource management a critical challenge in cities. The Internet of Things (IoT) offers transformative potential by networking sensors and devices throughout urban infrastructure. A growing literature characterizes

IoT as a worldwide network of interconnected objects that collect and exchange data to improve system performance. In smart cities, data-driven networks underpin optimized services, enable real-time monitoring of traffic, energy, water, and air quality, informing adaptive decision-making

that boosts sustainability and quality of life. For instance, by continuously monitoring energy use and environmental conditions, IoT can reduce waste and anticipate hazards before escalation (Nikpour et al., 2023). However, many early smart city initiatives have been technology-led, prioritizing efficiency over people. Critics note that such “technocentric” approaches often overlook social equity and citizen well-being (Hoang, 2024). The gap has led to human-centered IoT strategies that integrate community input at every stage. The present study examines how IoT can enhance urban services and how a participatory, citizen-centric approach can reorient smart cities toward inclusivity and resilience. Pioneering case studies have been reviewed and proposed a Citizen-Centric Standardization Protocol (CCSP), a set of best practices and standards to guide ethical, inclusive IoT deployments. By emphasizing co-creation, transparency, and adaptive feedback, CCSP aims to ensure that future smart city technologies genuinely serve citizens’ needs.

## 2. IoT-Enabled Smart City Solutions

IoT technologies enable connected urban systems that collect and analyse data in real time, transforming traditional city services into intelligent networks. Key applications include the following:

- **Smart Traffic Management:** IoT-based traffic control systems use cameras, vehicle sensors, and connected signals to optimize flow of traffic. By adjusting signal timing based on live data, such systems reduce congestion and idling. It will shorten travel time and lowers vehicle emissions proving cutting congestion directly that cuts carbon output by minimizing idle time (Rangarajan and Al-Quraishi, 2023). Advanced systems
- can also detect accidents or hazards and reroute traffic dynamically. In practice, cities deploying IoT-driven traffic control have reported smoother flows and safer streets.
- **Intelligent Lighting Systems:** Public lighting is a major energy consumer in cities. Smart streetlights equipped with motion and ambient light sensors can adjust brightness accordingly. Studies show that IoT-enabled LED lighting can slash energy usage by roughly 30–50% via intelligent control (Oroos & Mondal, 2023). For example, Barcelona’s network of LED lamps automatically dims when streets are empty or during daylight. Beyond energy savings, such lighting enhances safety by ensuring well-lit public spaces when needed. However, researchers caution that smart lighting rollouts must consider equity; some analysts warn that surveillance capabilities of connected lights could disproportionately impact vulnerable neighbourhoods unless privacy and access are explicitly addressed (Hoang, 2024).
- **Energy-Efficient Buildings:** Modern buildings increasingly incorporate IoT sensors for temperature, occupancy, lighting, etc. linked to automated management systems. Such systems enable predictive climate control and maintenance. A recent review finds that IoT-integrated building management can cut energy consumption by up to ~30%, yielding significant cost savings (Nikpour et al., 2023). For instance, smart meters and HVAC sensors continuously monitor usage patterns and adjust heating or cooling only when and where needed. It not only reduces wastage but also improves occupant comfort. Over time, large-scale deployment of such “smart building”

technologies across a city can markedly lower overall energy demand and emissions.

- **Waste Management Systems:** Smart waste systems use IoT sensors on bins and containers to signal fill levels. When a bin nears capacity, it automatically notifies city services, which then dispatch collection vehicles only when needed. This dynamic scheduling eliminates unnecessary pickups and shortens routes. In practice, sensor-based routing has cut operational costs by 20–30% in pilot programs, while also reducing fuel use and attendant emissions (**Oroos & Mondal, 2023**). Moreover, some smart bins can detect the type of waste deposited, enabling better recycling sorting. By combining fill-level alerts with GPS-enabled trucks, cities can greatly improve the efficiency and sustainability of waste collection.
- **Environmental Monitoring:** Distributed IoT sensors track urban environmental conditions air pollutants, water quality, noise, etc. around

the clock. Such sensors provide real-time data for authorities, enabling timely public health interventions and policy responses. For example, networks of air-quality sensors in cities can immediately flag unsafe pollution levels and help to shape clean-air zones as reported by **Bibri et al., 2023**. According to recent reviews, “smart city” IoT deployments commonly include environmental arrays, since continuous monitoring (24/7) gives policymakers up-to-date situational awareness. Singapore’s SG Clean initiative, for instance, uses IoT air monitors to inform citizens and officials of current particulate and NO<sub>2</sub> levels. In water systems, IoT probes measure parameters like pH and contaminants, aiding in early detection of water pollution. Overall, IoT sensing systems are critical for urban resilience: by promptly detecting hazards like flooding, smog, chemical spills etc., city managers can mitigate loss and protect public health.

**Table 1:** Key IoT Applications in Smart Cities and their Benefits.

| IoT Application               | Implementation   | Benefits   |
|-------------------------------|--|--|
| <b>Traffic Management</b>     | Sensors and cameras monitor roads; dynamic signal control and rerouting  | Reduces congestion and idle time, cutting vehicle emissions; improves traffic flow and safety      |
| <b>Smart Street Lighting</b>  | LED streetlamps with adaptive brightness and motion sensors              | Cuts streetlight energy use (often ~30–50%); enhances nighttime visibility and safety              |
| <b>Smart Buildings</b>        | Integrated HVAC, lighting, and occupancy sensors with automated controls | Lowers building energy consumption (by up to ~30%); reduces utility costs; improves indoor comfort |
| <b>Smart Waste Collection</b> | Fill-level sensors on bins; GPS-enabled dynamic routing                  | Reduces collection costs and fuel use; increases recycling rates via timely pickups                |
| <b>Environmental Sensing</b>  | Distributed air, water, noise, and soil sensors                          | Enables real-time pollution/water-quality alerts; informs rapid response and policy interventions  |

### 3. Toward a Citizen-Centric IoT Framework

While the above IoT systems can vastly improve efficiency, their social impact depends on governance. Traditional smart city projects have often been “tech-first,” neglecting public input (Hoang, 2024). A citizen-centric approach contrasts with this by putting residents at the core of design and decision-making. In a citizen-centered model, participatory platforms and human-centered design ensure that IoT deployments address local priorities. Research shows that active citizen participation enhances urban resilience and equity (Bibri et al., 2023). Co-creation processes – where communities help to define data collection goals and use the results – fostering trust and ownership. Key principles include inclusivity ensuring all groups can engage, transparency (open data and clear usage), and accountability in data handling.

In practice, It includes complementing sensor networks and analytics with continuous feedback loops. Rather than solely optimizing system metrics, a citizen-centric IoT framework emphasizes human values like well-being, fairness, and privacy. Survey of smart city projects highlights that “citizen-centered cities are urban environments designed to prioritize the needs, aspirations, and well-being of their inhabitants”. In such cities, technology serves as a tool to enhance quality of life, not as an end in itself. Tools like Barcelona’s Decidim or blockchain voting platforms exemplify the shift using digital forums to let residents propose and prioritize projects (including IoT initiatives), ensuring that technological solutions align with community goals. By embedding participatory design and open governance from the outset, cities can avoid scenarios where residents feel excluded by top-down implementations. The result is a more inclusive smart city, where advanced

infrastructure works in tandem with empowered citizens rather than at their expense.

### 4. Case Studies: Citizen-Led IoT in Action

Smart cities seeking sustainability and equity have started citizen-driven IoT projects. Three illustrative cases have been reviewed below that highlight different engagement models.

**4.1 Barcelona’s Decidim Platform:** A world leader in digital democracy, Barcelona launched *Decidim* (“We Decide”) in 2016 as an open-source platform for participatory budgeting. Through Decidim, city residents collectively chose which municipal projects to fund. In the latest cycle, citizens directed €30 million of public budgets using Decidim. Notably, some of these projects funded IoT infrastructure. For example, voters supported installing adaptive LED streetlights in underserved neighbourhoods. The connected lamps automatically dim when areas are vacant, significantly reducing energy use (studies suggest more than a 50% drop in lighting power) while maintaining safety. Other citizen-backed initiatives included IoT-enabled waste bins: sensors in public garbage cans now notify trucks only when bins are full, streamlining routes and cutting fuel consumption. Such examples illustrate budgeting transparency and local input can direct technology where it is most needed. Barcelona’s experience shows that participatory IoT projects build public trust and improve service outcomes. It means co-created projects tended to be implemented more effectively, though challenges remain in ensuring broad participation and clear communication of data use.

**4.2 Amsterdam’s Smart Citizens Lab:** Launched in 2014, Amsterdam’s *Smart Citizens Lab* empowers residents as co-researchers of the urban environment. Using low-cost open-source sensor kits, volunteers measured hyperlocal data on air quality, noise, and humidity. For instance,

citizens used portable devices to log carbon monoxide and NO<sub>2</sub> levels around their homes. These grass-roots data collection efforts revealed previously unseen pollution hotspots in the city. The findings directly informed policy: Amsterdam expanded low-emission zones and green corridors in response to the localized air-quality data. Beyond environmental insights, the project forged new ties between communities, scientists, and policymakers. As one report notes, “by giving individuals tools to conduct research, increase the involvement of public in the immediate environment”. In other words, citizen science in Amsterdam led to greater engagement and co-ownership of urban problems. A key lesson is that while distributed sensing produces valuable insights, it also poses challenges of data accuracy and scale. Ensuring the technical robustness of DIY sensors and effectively integrating citizen data with official systems remain ongoing tasks.

#### 4.3 Songdo’s Blockchain Voting Initiative:

Songdo (South Korea) was designed as a greenfield smart city, but initial deployments were technology-driven with little citizen input. In 2020, Songdo experimented with a blockchain-

based voting platform to involve residents in IoT planning. Citizens could vote securely on proposed infrastructure projects (e.g. flood-monitoring sensors, smart energy grids). The initiative aimed to increase transparency and trust in smart city decision-making. Preliminary reports suggest the blockchain system improved public confidence by publicly recording votes and outcomes. For example, citizens prioritized installing river-level sensors, and the city later reported enhanced flood response times as a result. Similarly, feedback from the vote led to expansion of the IoT-powered electrical grid, which optimized power distribution and reduced overall energy wastage. Although peer-reviewed data for exact figures is not available, early findings are similar with research showing that transparent citizen input can reinforce trust in urban IoT systems. Songdo’s experiment leads to the fact that technology alone is not enough engagement tools ( like blockchain voting) are needed to legitimize IoT plans. Digital literacy and access are critical continues to work on making its participation platform user-friendly for all demographic groups.

**Table 2:** Summary of Case Studies.

| City             | Citizen Engagement              | IoT Projects  | Outcomes and Impacts  |
|------------------|---------------------------------|---|---|
| <b>Barcelona</b> | Decidim participatory budgeting | Adaptive LED streetlights, Smart waste bins                             | LED streetlights will slash energy consumption by a huge margin; smart bins will maximize pickups and consequently lower emissions; building public trust in urban initiatives. |
| <b>Amsterdam</b> | Smart Citizens Lab              | Amsterdam Portable air quality (NO <sub>2</sub> / CO) and noise sensors | Citizen-measured pollution maps indicate hotspots; policy-making (new low-emission zones); more collaboration between the citizens and scientists                               |
| <b>Songdo</b>    | Blockchain voting platform      | Flood sensors to monitor water, Smart energy grids                      | Improved transparency of IoT decisions; expanded smart grids optimized power (e.g., load balancing) reducing waste.   |

## 5. Emphasizing Citizen-Centric Standardization for Smart City Success

Based on the above case studies, Citizen-Centric Standardization Protocol (CCSP) has been developed to guide smart city IoT deployment. CCSP is built on four core pillars:

1. **Co-Creation via Digital Platforms:** Encourage tools like Barcelona's Decidim and blockchain-based voting so that citizens participate at every stage – from ideation to governance. Co-creation ensures urban innovations, solve problems identified by the community. Participatory budgeting has demonstrated that residents will fund sustainability projects they co-design. Digital platforms should be open-source and interoperable (based on FIWARE standards) to avoid vendor lock-in and to facilitate knowledge sharing.
2. **Ethical AI and Transparent Governance:** Embed fairness, accountability, and human rights into IoT analytics. AI algorithms used in smart services must be trained on diverse, representative datasets and subject to regular auditing to prevent bias. Transparency is essential: decision-making processes (such as traffic-control algorithms or resource allocations) should be explainable to the public. International guidelines (ITU-T Y.4471) stress that smart city AI systems should be free of prejudice and should safeguard privacy. By making AI ethics non-negotiable standards, CCSP ensures algorithms serve the public equitably.
3. **Decentralized Data Sovereignty:** Shift data control from centralized entities to individuals. CCSP promotes blockchain, federated data architectures, and self-

sovereign identity (SSI) so that residents truly own and manage their information. For instance, blockchain-based data registries can give users cryptographic control over sensor data they generate, and SSI systems enable portable identities across services. Such decentralized models enhance security and trust by minimizing single points of failure. Research notes that moving from centralized databases to “distributed data governance” democratizes data use in smart cities. Open data standards and federated analytics also facilitate interoperability across vendors and city departments, avoiding fragmented data silos.

4. **Adaptive Feedback Integration:** Establish ongoing feedback loops between citizens and city systems. IoT deployments should incorporate channels (mobile apps, community sensors, public dashboards) through which residents can continuously report issues, suggest improvements, and can check outcomes. This creates a dynamic cycle: sensor networks and administrative data drive services, which are constantly tuned by citizen-generated insights. For example, real-time feedback apps might allow commuters to report congestion hot spots, which then automatically adjust traffic signals. This pillar ensures that smart city solutions remain flexible and responsive to changing human needs.

CCSP moves beyond “black box” implementations by explicitly embedding equity and resilience. It advocates standardizing IoT platforms so that cities can mix-and-match compatible modules. By insisting on open-source frameworks and

interoperability, CCSP reduces vendor lock-in and technology fragmentation. Moreover, decentralized governance as envisioned by CCSP breaks down data monopolies, giving communities a stake in innovation. To succeed, two systemic shifts are needed: (a) collaborative policymaking, e.g. city councils forming empowered citizen advisory boards (as in Barcelona), and (b) equity-focused funding, such as grants for underserved neighbourhoods to co-design IoT solutions. Endorsements by international bodies (e.g. ITU, ISO) can help codify these principles, making transparency and data rights integral to smart city standards.

## 6. Adoption of Emerging Technologies and Implementation Hurdles

The CCSP framework can be greatly enabled by emerging technologies, but also pose certain challenges. Ultra-fast 5G networks provide the high bandwidth and ultra-low latency needed for real-time IoT integration (**Mahomed & Saha, 2025**). For example, 5G lets thousands of citizen smartphones and sensors stream data simultaneously, improving services like live traffic rerouting. A recent review explained that 5G “delivers unmatched speed, extremely low latency, and broad device connectivity,” facilitating seamless IoT device integration and intelligent applications. In practice, cities using 5G have achieved near-instantaneous coordination of traffic lights and emergency systems.

Edge computing complements this by processing data close to its source. Instead of sending all raw sensor data to a central cloud, analysis happens on local gateways or devices. This approach dramatically improves privacy and resilience (**Khanna et al., 2022**): by keeping sensitive data

(like video or health readings) on-device, edge computing “protects user privacy better than uploading raw data to the cloud”. It also reduces network congestion and latency, as only refined insights are transmitted upstream. In a CCSP-aligned city, edge nodes would handle citizens’ personal data securely while sharing anonymized summaries with the cloud, thus balancing usefulness with confidentiality.

Ethical AI is another critical enabler. When machine learning models in smart city applications are developed on inclusive datasets, that can optimize services without marginalizing any group. For example, an AI transit planner trained on diverse travel patterns will better serve low-income neighbourhoods. CCSP calls for transparent AI: algorithms used for public resource distribution or law enforcement must allow auditing and appeal processes. While few off-the-shelf citations exist for “ethical AI in smart cities,” numerous guidelines (like the ITU’s 2020 recommendations) underscore the importance of fairness and accountability (**Bibri et al., 2023, Hoang, 2024,**) in urban AI systems.

Blockchain and Self-Sovereign Identity (SSI) technologies support data decentralization. Blockchain’s immutable ledgers can underpin transparent city records or participatory votes (as in Songdo). SSI frameworks (used in Estonia’s e-Residency, for instance) let individuals verify their identity across services without sharing all personal data (**Khanna et al., 2022**). These tools promise that citizens truly own their data footprint in the city. CCSP envisions giving each resident a personal data vault or identity wallet, from which they grant (and revoke) access to city apps, reinforcing data sovereignty.

Despite the benefits, several hurdles can also be addressed:

- **Interoperability:** Integrating new technologies with existing infrastructure can create fragmentation. Without common standards, each department's IoT system may not talk to another. As one analysis warns, uncoordinated adoption can lead to incompatible **“data islands,”** undermining the very promise of comprehensive smart services. CCSP stresses open standards to avoid this pitfall.
- **Privacy and Surveillance Risks:** Expanding sensors and connectivity heightens concerns of constant surveillance. Without strict governance, data collected for “public good” can be misused. Privacy scholars (**Zoonen et.al., 2016**) highlight that pervasive city monitoring may erode civil liberties if unregulated. CCSP's emphasis on citizen control (via SSI and edge processing) aims to mitigate such risks, but robust legal safeguards are still required.
- **Digital Divide:** Smart city benefits can only reach all residents if access is equitable. Marginalized communities risk exclusion due to internet access or digital skills. UN-Habitat reports and other studies emphasize that technology-led urbanism often overlooks vulnerable populations. CCSP therefore calls for digital inclusion programs (public Wi-Fi, training centres, subsidized devices). As one review notes, citizen-centric cities must ensure *inclusivity* – **“access to resources and opportunities for all residents regardless of background”**.
- **Investment Barriers:** Deploying 5G infrastructure, citywide IoT networks, and securing ethical AI development requires significant funding. Many municipalities face budget constraints. Public–private

partnerships and green bonds may help, but cities must align such investments with social equity goals. CCSP suggests dedicated grants for community-driven projects to ensure that even low-income areas become smart-city innovators.

- **Technical Bias and Accountability:** Finally, AI and big data systems can inadvertently encode biases (e.g., if traffic models favor affluent districts). CCSP recommends regular algorithmic audits. Without such checks, smart services risk reinforcing inequalities. In short, the CCSP framework acknowledges that technology alone is insufficient; inclusive oversight mechanisms must be built in to ensure smart city tech truly serves everyone.

Overall, the convergence of 5G, edge computing, AI, blockchain, and SSI provides powerful tools for CCSP, but only if matched with governance reforms. As one expert observes, realizing a fully adaptive, citizen-centric smart city requires not just innovation but “the ability to make effective and precise decisions in the shortest possible time”, enabled by human–machine collaboration.

## Conclusion

The future of urban development depends on harmonizing advanced technologies with human-centered governance. IoT innovations – from smart grids to environmental sensors – can greatly improve resource efficiency and quality of life. However, protocol is successful only when citizens are active partners. The proposed CCSP framework illustrates how combining co-creation, ethical AI, decentralized data rights, and continuous feedback can transform smart cities into equitable, resilient ecosystems. Addressing systemic barriers (interoperability, privacy,

equity) is essential: international standards and collaborative policymaking must mandate transparency and inclusion as core principles. By prioritizing citizen agency, cities can ensure that every sensor and algorithm enhances, rather than undermines, community well-being. In sum, smarter infrastructure must be paired with smarter collaboration between people, policymakers, and technology. The CCSP is offered as a guiding protocol to achieve balance, turning the smart city vision into a truly people-powered reality.

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## **IOT-ENABLED INFRASTRUCTURE FOR SUSTAINABLE URBAN DEVELOPMENT...**

# PHYTOCHEMICALS OF MEDICINAL PLANTS AND THEIR VERSATILE PHARMACOLOGICAL PROPERTIES

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## Abstract

Plants have been in use for treating various ailments from the prehistoric times and continue to be the source of more than 25% of present range of prescribed drugs. There is growing interest towards alternative therapies using plants derived products. Phytochemicals of medicinal plants such as alkaloids, flavonoids, tannins, cardiac glycosides, terpenes, nitrogen containing compounds form the basis of their versatile pharmacological activities. They play an immeasurable role in health care and disease prevention owing to their antioxidative, anti-inflammatory, anti-aging, antiviral, anticancer, anti-thrombosis and immune-regulatory potential. The review highlights the different categories and potential therapeutic applications of plant metabolites.

**Keywords:** Medicinal plants, Secondary metabolites, Phytochemicals, Pharmacological activities.

## Introduction

According to World Health organization, a plant is claimed to have medicinal importance if it contains a substance which may be used as a therapeutic agent or as a precursor for semi synthetic drugs. Use of plant leaves, bark, fruit, seeds or roots for various medicinal purposes is referred as Herbal medicine or Phytomedicine. Plants are being specifically employed for therapeutic applications, due to their affordability and fewer side effects. With advancement of Iatrochemistry in 16th century, plants had become the most important source of prophylaxis as well as treatment of several diseases (Ahmed et al., 2017).

Earlier Medicinal plants were used as simple formulations like infusions, decoctions and macerations [Bauer, 2012]. During early 19<sup>th</sup> century, discovery and isolation of alkaloids from plants marked the start of 'Scientific Pharmacy'.

Advancements in chemical methods and various isolation techniques, led to the discovery of other bioactive substances like glycosides, Tannins, etheric acid, phenolic compounds, terpenes, vitamins and hormones from medicinal plants. [Bauer, 2012]

Numerous studies over the last decades have demonstrated these substances play an important role in physiological regulation, health care, and disease prevention owing to their antioxidative, anti-inflammatory, antiaging, antiviral and anticancer properties (Spiller et al., 2008; Yi Z et al., 2004; Puneet et al, 2013). They have also been reported for their role in lipid profile & immune regulation, cardiovascular protection and improvement of metabolic functions.

The medicinal properties attributed by the plants are mainly due to the secretion of the secondary

metabolites. Plants possess limitless ability to synthesize secondary metabolites, such as tannins, alkaloids, coumarins, glycosides, saponins, flavonoids, phenols, quinones, many aromatic substances and various types of oxygen substituted derivatives (Kumar et al., 2013). The isolated secondary metabolites are very effective in the treatment of several deadly and life threatening diseases (Behl et al., 2021). Natural drugs derived from plants are gaining popularity because of fewer side effects, lesser cost, better patient tolerance and wide acceptance due to a long history of use. This article reviews the classification and biochemistry of phytochemicals, occurrence and biosynthesis in plants, biological activities and implications for human health and various diseases.

### **Classification, structure and functional properties of Secondary metabolites**

Secondary metabolites are a group of organic compounds which are produced in small amounts and do not have any direct role in processes like photosynthesis, respiration, protein synthesis, nutrient assimilation and formation of Carbohydrates, proteins and lipids. In most of cases functions of secondary metabolites are still unknown but these are majorly believed to play a role in survival, reproduction, attracting seed pollinators and also in influencing plant growth. They also help plants in adapting to sudden changes in temperature, light and draught conditions etc. (Kroymann 2011; Ramakrishna & Ravishankar, 2011).

In industries these are used as gums, flavour enhancers, as aromatic compounds, as insecticides and herbicides (Hall et al., 2008; Freeman et al., 2008). Many of secondary metabolites are used in pharmaceutical industry owing to their large number of Pharmaceutical activities. Secondary

metabolites are classified based on their chemical structure, presence or absence of Nitrogen, solubility in the solvents and their biosynthetic pathways. (Hall et al., 2008).

### ***Terpenes (isoprenoids)***

These are a largest group of secondary metabolites in plants containing more than 40000 different molecules. These do not contain fatty acids and their basic structural unit is isoprene molecule that is why also known as isoprenoids. Depending upon the number of isoprene units in their structure, these are classified into monoterpenes (2 isoprene units), sesquiterpenes (3 isoprene units), triterpenes (6 isoprene units), tetra terpenes (8 isoprene units). Most common are hemiterpenes which contains single isoprene unit and five carbons in their structures are volatile products which emerged from tissue that are photosynthetically active (Paul 2009). In most of plants terpenes are present in fruits and flowers e.g. in lemon, mint, eucalyptus, great basil and is responsible for aroma. Terpenes play a role in both primary and secondary metabolism. These act as a photosynthetic pigments (carotene), as electron carrier (ubiquinone and plastoquinone) and also act as a plant growth and development regulator (gibberellins) and as phytosterols, part of cell membrane. They also play a role in secondary metabolism as defensive molecules and act as toxic compounds for insects. They have a role in attracting pollinators in some plants (Trapp and Croteau, 2001; Veitch et al., 2008).

These are synthesized by mevalonic acid pathway and methylerythritol pathway. In mevalonic acid pathway, mevalonic acid is formed by condensation of three molecules of acetyl coenzyme A which then reacts to form isopentenyl diphosphate, this pathway occurs in cytosol where as methylerythritol pathway take place in chloroplast (Tiago et al, 2013).

### *Phenolic compounds*

These compounds contain a hydroxyl group linked to an aromatic hydrocarbon. Phenol is simplest representative member of this group. These are classified based on the number of carbon atoms in their molecules. On this basis these are mainly classified into phenolic compounds (substituted phenols), acidic phenol compounds (A carboxyl group substituted on phenol), acetophenone (rarely found in nature), cinnamic acid, cinnamyl aldehydes, cinnamyl alcohols (commonly found as esters of quinnic acid), flavonoids, bioflavonoids, benzophenone (aromatic ketones), Xanthin, quinones, betacyanins and polymer compounds such as lignans and neoliganins, tannins are more complex structurally (Seabra et al, 2006). These are produced in plants by Shikimic acid pathway and poly mevalonate/ acetate pathway (Morante-Cariel et al., 2024) or in some cases by precursors which take part in both Pathways (e.g. production of flavonoids). Cinnamic acid, phenylalanine and their derivatives are mainly synthesized by shikimic pathway. Quinones and xanthones are synthesized by poly Acetate pathway (Vattem et al, 2005).

Phenolic compounds act as antioxidants, plant growth inhibitors, phenols accumulated in seeds act as a filter to oxygen to prevent it from reaching embryo and inhibiting its germination. Phenols accumulated on surface of plant leaves captures about 90% of UV radiation. These also provide aroma and color to fruits and are also important in favoring the dispersion of seeds. Phytoalexins are toxic to microorganism, playing a role in defending plant against various microbial infections. These also takes part in providing protection to plants by producing bitter flavour and textures that are very unpleasant to herbivores (Karen et al, 2019).

### *Alkaloids*

Are large group which constitutes compounds primarily isolated from the vascular plants. Different parts of a plant have different concentration of alkaloids and some parts of plants does not contain alkaloids at all (Ng et al, 2018). These are also present in bacteria and animals. These contains nitrogen in their structures, are toxic in nature and response to numerous precipitation reaction. These are classified on basis of their biosynthetic origin, presence of heterocyclic nucleus in their structure, their Pharmaceutical activities and distribution in different plant families. Out of these bio synthetic origin of alkaloids has been used for their classification most often (Kumar, S. 2014).

According to their bio synthetic origin these are classified as true alkaloids, proto alkaloids and pseudo alkaloids. Most of the alkaloids found in plants belongs to pure or true alkaloids. These contain a nitrogen atom in their cyclic ring and are basic in nature and are highly reactive even in small amounts. These are found free in plants but in some cases these are present as salts. Amino acids like L-ornithine, L-lysine, L-tyrosine and tryptophan are precursors for their synthesis (Kumar, S. 2014). Some of them are also derived from anthranilic acid and nicotinic acid. They are also used as anticholinergic drug. Nicotine, atropine and morphine belong to true alkaloids.

Proto alkaloids do not contain nitrogen atom in their structure and are derived from tryptophan an ornithine. There are also referred to as aromatic amines. Mescaline is used as a hallucinogen, Hordenine used as a stimulant of central nervous system and Ephedrine is employed as a stimulant of sympathetic nervous system (Babbar 2015).

Pseudo alkaloid contains nitrogen in their

heterocyclic ring but are not synthesized from amino acids. They are mainly produced by incorporation of Nitrogen into compounds which do not contain nitrogen. Terpenic alkaloids are example of these pseudo alkaloids. They play a role in defending the plant against insects and herbivores owing to their toxicity and deterrent activity (Kumar, S. 2014). They also play a role in protecting the plants from microorganisms or predators and also act as allopathic substances. Aconitine is highly poisonous and theobromine used as central nervous system stimulator.

### ***Steroids***

These are triterpenes or triterpenoids. This group of compounds which contains 30 carbon atoms in their structure and are usually produced by polymerisation of isoprene units. These have a basic structure which is formed by fusion of 5 member rings and the three 6 member rings. Cortisol and testosterone are commonly occurring steroids (Cheng et al., 2025). On basis of their chemical structure (side chain attached to the ring), site of production, biological function and the molecular actions, biochemical effects these are classified into two different categories – Phytosterols and brassinosteroids. Phytosterols are used as a food additives, used in medicine and cosmetics and also found to exhibit cholesterol reducing activities and also may act in Cancer prevention and are widely used as component in livestock dietary supplement (Holm et al, 1996). Pregnene, brassinosteroid found to be an inhibitor of mitochondrial action chain (Julie et al, 2011).

### **Pharmacological activities of Secondary Metabolites**

Plants have a vast potential for their use as curative medicine. There are evidences that herbs had been used for a wide range of potential

therapeutic applications in the Indian, the Greek, the Chinese, the Egyptian and the Roman civilizations. In India, medicinal plants are in use till date by all sections of people either as folk medicines in different indigenous systems of medicine like Ayurveda and Sidha from very ancient times or in the pharmaceutical preparations (Srinivasan et al., 2001).

Secondary metabolites exhibit diverse biological activities ranging from anti-inflammatory, antioxidant, anti-diabetic, anti-cancer, anaphylactic, antibiotic, antifungal, antiviral, and many more.

### ***Therapeutic applications of Phenolic compounds***

The phenolic compounds are well known for their medicinal potential. Quercetin, has been reported to exhibit anti-inflammatory properties (Tsao et al., 2022; Meenakshi et al., 2024), Silybin exhibit antihepatotoxic activity, Gerilesin and daidzein exert phyto estrogenic activities and naringenin shows insecticidal properties (Goławska et al, 2014; Huang et al., 2024). Another member of the group, Gallic acid (phenolic acid) has been reported for anti-inflammatory, antitumor, antifungal, antibacterial, anti anaphylactic and antiviral activities. It is also known to play a role in inhibiting degradation of insulin and in promoting relaxation of smooth muscles (Harborne and Baxter, 1993).

Some examples of plants exhibiting Pharmacological activities because of presence of phenolic compounds are: *Arctostaphylos uva-ursi* exhibits antimicrobial activity (Eric Y. 2020), *Capsicum spp* shows circulatory stimulant activities and analgesic activities because of presence of capsaicinoids phenolic compound (Spiller et al, 2008). Antihelminthic activities of *Dryopteris* are also because of simple phenolic

compounds in them. Geraniin (Tannin) derived from *Geranium robertianum*, Tellimagrandine derived from *Quercus alba* exhibit anti-inflammatory activity (Yi et al, 2004). Drugs containing Tannins act as antidiarrheal and are also used as antidotes in poisoning caused by heavy metals and alkaloids. Epigallocatechin 3 gallate (principle compound in tea) shows anti-angiogenic activities in mice and Ganberry (*Vaccinium oxycoccus*) has been employed as urinary antiseptic molecule (Puneet et al, 2013).

Flavonoids are known for their anti allergic, anti-inflammatory, vasoprotective and tumor inhibiting properties. Xanthones and chromones are mainly found in Gentianaceae family. *Polygalanyikensis* root exhibit antifungal activity due to presence of Xanthones (Susana et al, 2011). Stilbenes a small group of secondary metabolites are para hydroxylated compounds and exhibits estrogen like activities and are mainly found in pinus and picea. Lignans like dibenzyl butyrololol exhibits cytotoxic activities (Gehm et al, 1994; Rana et al, 2022).

#### **Therapeutic applications of Alkaloids compounds**

Acridones, quinolones, purines, pyridines, pyrrolidines, oxindoles, imidazoles, carbolines, ergots are basic type of alkaloids (Tadeusz 2015). They exhibit a diverse range of pharmacological activities including respiratory stimulation and vasoconstriction, toxicity as well as hypertensive and hypotensive effect. Vinblastine (*Catharanthus roseus*) has been used for treating diabetes and as a disinfectant. Caffeine found in *Coffea spp*, *Camellia sinesis*, *Cola acuminata* acts as a Central nervous system, respiratory, cardiovascular stimulant and a diuretic agent. Nicotine derived from *Nicotiana tobacum* acts as a tranquilizing agent and is highly toxic leading to respiratory

paralysis at extreme high doses (Benowitz, 2009).

Saponins mainly exhibits anti-tumor, spermicidal, sedative, expectorant and analgesic properties. Glycyrrhizin (derived from *Glycyrrhiza glabra*) acts as an expectorant agent, used for treatment of cirrhosis and hepatitis. Roots of *Phytolacca americana* and *Bupleurum falcatum* exhibits anti-inflammatory properties (Güçlü and Mazza, 2007).

#### **Therapeutic applications of Terpenes**

Monoterpenes are a very important component of Essential oils derived from plants. They have a diverse medicinal uses. Compounds like menthol and camphor used as anti itching and analgesic agents and various monoterpenes also known to exhibit anti helminthic activities. Sesquiterpenes from *Vernonia calarata* exhibits antiamebic properties. *Atractylodis* rhizoms are used as a source of anti-inflammatory, analgesic and diuretic compounds. Vitamin k1 is a diterpene which function as a anti-hemorrhagic compound. Vitamin A is a diterpene which is also known as carotene. Diterpenes derived from *Kalmia latifolia* exerts anti-feedant properties (Bagci et al, 2010). Boswellic acid derived from *Boswellia carterii* reported to exhibit anti-inflammatory and anti-rheumatic activities (Culioli et al, 2003).

Glycerin oleate, a Polyunsaturated fatty acids found in oils derived from plants are known to exhibit anti-inflammatory, antioxidant activities and also are used as prophylactic agent to decrease the risk of cardiovascular diseases. *Jajoba* liquid wax obtained from *Simmondsia chinensis*, used as an anti aging, anti inflammatory agent also exerts wound healing properties (Subramaniam et al, 2011). It is also used in sunscreens and moisturizers. Essential oils derived from plants are also used as antimicrobial, anti-inflammatory,

antiseptic and anesthetic remedies.

### ***Plant derivatives as anti-cancer agents***

Plant derivatives which are being effectively used as antiproliferative compounds in cancer chemotherapy include Vinca alkaloids (Vincristine and vinblastine), taxanes (Paclitaxel) (Zhao et al., 2022), camptothecin (topotecan and irinotecan)

and epipodophyllotoxins (eyoposide). Phenolic compounds including phenolic acid, flavonoids and tannins exhibit potential anticancer activity which is attributed to their ability to arrest cell cycle, inducing apoptosis, inhibit cell proliferation and angiogenesis. Some of the phytochemicals which are used as anticancer agents are mentioned in **table 1**.

**Table 1-** Phytochemicals and their application as anticancer agents.

| Phytochemicals         | Source (Plant Name)         | Family Name   | Plant part used | Therapeutic Use             | References            |
|------------------------|-----------------------------|---------------|-----------------|-----------------------------|-----------------------|
| 5-Fluorouracil         | <i>Withaniasomnifera</i>    | Solanaceae    | Roots           | Cervical cancer             | Yadav et al., 2010    |
| Vindesine              | <i>Catharanthus roseus</i>  | Apocynaceae   | Bark, Leaves    | Leukemia, testicular cancer | Cragg & Newman, 2005  |
| Vincristine            | <i>Catharanthus roseus</i>  | Apocynaceae   | Bark, Leaves    | Lymphocytic leukemia        | Atkinson et al., 2010 |
| Vinblastine            | <i>Catharanthus roseus</i>  | Apocynaceae   | Bark, Leaves    | Lymphocytic leukemia        | Di´eras et al., 2008  |
| Colchicine             | <i>Colchicum autumnale</i>  | Colchiciaceae | Leaves          | Multiple solid tumors       | De Bono et al., 2010  |
| Larotaxol              | <i>Taxus baccata</i>        | Taxaceae      | Bark, Leaves    | Breast, bladder cancer      | Biba et al., 2013     |
| Paclitaxel             | <i>Taxus brevifolia</i>     | Taxaceae      | Bark            | Breast and ovarian cancer   | Ayoob et al, 2017     |
| Bullatacin             | <i>Annona squamosa</i>      | Annonaceae    | Seeds           | Liver cancer                | Efferth 2017          |
| Bryophyllin A          | <i>Bryophyllum pinnatum</i> | Crassulaceae  | Leaves          | Cervical cancel             | Tariq et al, 2017     |
| Tannins                | <i>Debregeasia saeneb</i>   | Asteraceae    | Roots           | Internal tumors             | Pahari et al, 2016    |
| Solamargine            | <i>Solanum nigrum</i>       | Solanaceae    | Leaves          | Liver, Lung, skin cancer    | Tu et al, 2016        |
| Xanthatin              | <i>Xanthium strumarium</i>  | Asteraceae    | Fruits          | Lymphocytic leukemia        | Rastogi et al, 2010   |
| Thymoquinone           | <i>Nigella satava</i>       | Ranunculaceae | Seeds           | Colon, prostate cancer      | Tsai et al, 2012      |
| Kaempferol galactoside | <i>Bauhinia variegata</i>   | Fabaceae      | Flower          | Ovary, cervix, colon cancer | Osman et al, 2015     |
| Skimmianine            | <i>Aegle marmelos</i>       | Rutaceae      | Stem bark       | Colorectal cancer           | Shin et al, 2015      |
| Curcumin               | <i>Curcuma longa</i>        | Zingiberaceae | Rhizomes        | Colon cancer                | Sun et al, 2015       |

## Conclusion

Plants have been instrumental for treatment of various ailments since a long time and are still under research for discovery of novel drugs candidates. They are often used in combination with conventional treatments or as natural supplements to enhance health and well-being. By harnessing the therapeutic potential of plants and their derivatives, scientists aim to develop new drugs that offer improved efficacy, safety, and specificity. The continued research into the effectiveness and bioavailability of phytochemicals will likely expand their applications in clinical settings, offering natural and complementary options for managing diseases.

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