

# AWARENESS

*Newer Horizons in Human Excellence*





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## Table of Contents

1. The Onslaught of Artificial Intelligence in Healthcare — Kanwaljeet J. S.Anand and Shaun P. Setty	1
2. Indian Jews:A Case Study of Unique Religious Tolerance — Nicole Hirschhorn	7
3. IXOHOXI Magic Square in Pādukā Sahasram by Sri Vedānta Desika — N Kannan, K Srikanth	15
4. Advancements and Challenges in AlGaN and Phosphor-Based Deep Ultraviolet LEDs: Towards Broader Applications and Higher Efficiencies — K Vineela, P.V.N.M Kaushik, K. Jayanthi	21
5. Emotional Freedom Techniques (EFT) and Dopamine Detox:A Neurobehavioral Tool for Stress Management — Rajeshwari Ullagaddi	39
6. Confidence in Connectivity: Tracing Government Commitment through India's UDAN Scheme — Jacob Arndt	53



Editorial

## The Onslaught of Artificial Intelligence in Healthcare

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On January 4th, 2026, the Government Institute of Medical Sciences (GIMS, Greater Noida, New Delhi), inaugurated the first artificial intelligence (AI)-based urgent care clinic – taking a strategic step forward in integrating AI into the healthcare industry. In collaboration with IIT Kanpur, IIT Lucknow, and IIT Madras, this clinic is equipped to use artificial intelligence and genetic screening to detect and treat serious and chronic diseases such as cancer, heart, kidney, or liver ailments at an early stage.<sup>1</sup> By integrating routine diagnostic labs, imaging, and wearables with the patient’s genetic data through advanced algorithms and automation, this clinic aims to predict and possibly prevent diseases, start early treatment, assess response to treatment, and monitor recovery. This goal, though laudable and visionary, still lacks the details of how it will be accomplished and how hapless patients will be protected through this process. Distributive justice also demands that we examine the cost of implementing such an advanced program, or ask whether the extra funding might be used to help more patients with basic healthcare needs?

Despite the unbridled excitement, diverse efforts, and immeasurable investments for incorporating AI into healthcare, the “bystander effects” of this revolution remain unexplored and controversial. Currently lacking are the details for incorporating a patient-centered approach, its impact on patient-physician relationships, as well as the learning of medical students and trainees at all levels and in multiple disciplines. As medical professionals rooted in compassionate, patient-centered medical and surgical care at the bedside, we identify six key areas deserving of thoughtful debate and deliberation.

### 1. Algorithmic Bias and Health Inequities

Most of the current AI models are trained on non-representative patient datasets, which often lead to biased outcomes and flawed recommendations for the most marginalized groups. For example, models for detecting skin cancer were trained primarily on fair-skinned Caucasian populations and showed significantly lower diagnostic accuracy in people with darker skin.<sup>2</sup> AI algorithms developed in USA systematically prioritized healthier White patients over sicker Black patients because they used healthcare spending as a proxy for medical need, failing to account for the fact that poor patients have less access to medical care. Further, most patient datasets are obtained from urban American and Chinese populations, and generalizing these models to low-income or rural populations or other countries and regions may be fraught with the potential to worsen health inequities and healthcare delivery to marginalized groups.

### 2. The “Black Box” and Explainability

Advanced AI systems, like the deep learning models developed by major corporate entities, are like “black boxes” because their decision-making processes appear too complex for human interpretation<sup>3</sup>. Use of these AI algorithms is likely to undermine clinical trust among both doctors and patients. Many medical practitioners will not follow AI recommendations when the underlying logic is opaque, because this lack of explainability contradicts their underlying principles for practicing evidence-based medicine.<sup>4</sup> On the other side of physician-patient equation, using recommendations from an AI “black box” obviates the patient’s legal right to an explanation for the medical decisions that significantly affect their health coming from automated systems whose logic is unclear.<sup>4</sup>

### 3. Liability and “The Captain of the Ship”

Perhaps the most grievous concern is the question of who will be held responsible when the AI system makes a harmful error? Current malpractice and tort law typically holds the treating physician as the “captain of the ship” responsible and legally liable for errors, even if they were following flawed AI decisions. AI developers routinely issue disclaimers shifting the liability for following their automated decisions to the treating physicians, and are unwilling to take responsibility for the flaws that may be inherent in their algorithmic logic.<sup>5</sup>

Legal theories like FDA Preemption can further shield the developers of high-risk (Class III) devices from state-law tort claims if they have received formal premarket approval from the FDA, thus leaving patients and doctors with limited avenues for legal recourse. *Express preemption* means that the federal statute, namely the US Federal Food, Drug, and Cosmetic Act (FDCA) – explicitly includes a preemption provision that all or some state law is displaced. It also provides for an *implied field preemption* in cases where the statutory language is unclear, but the displacement of state law can be implied by Congress’s intent to occupy the area exclusively.<sup>6</sup> Further, it provides for *conflict preemption*, in cases where state and federal requirements contradict each other, and a party cannot comply with both.<sup>6</sup>

Oftentimes, sick patients don’t have the energy to read or the ability to understand the detailed disclaimers that they are asked to sign, and even busy practicing physicians would be unlikely to read through or comprehend the dense legal language that accompanies most disclaimers. At best, the regulatory oversight for legal consent while using AI algorithms involves a patchwork of existing data protection laws like the GDPR (General Data Protection Regulation) in the European Union, which

gives patients more control over their digital data and the DPDP Act in India (Digital Personal Data Protection Act, 2023), a comprehensive law for protecting the digital personal data of Indian citizens. Emerging, AI-specific regulations (like the EU AI Act) emphasize the key principles of informed and explicit consent, including transparency, human oversight, liability and accountability, especially for high-risk healthcare applications of AI. This law remains to be legally tested European courts.

#### 4. Data Privacy and “Bio-surveillance”

Along the same theme, significant ethical concerns exist about non-consensual data usage and the re-identification of patients from putatively “anonymized” healthcare datasets. Corporate partnerships where patient data is shared with tech companies without explicit patient notification or consent (e.g., Google’s Project Nightingale) are becoming more prevalent.<sup>7</sup> Using data scrubbed from social media, financial, educational, and commercial platforms, AI algorithms can easily re-identify some patients even from anonymized datasets, thereby exposing their sensitive genetic, physical or mental health information and creating the potential for discriminatory bias in diverse areas like bank loans, employment, or health insurance.<sup>8</sup>

#### 5. Erosion of the Patient-Provider Relationship

By eroding the quality of patient interactions, there are growing public and professional concerns that AI will dehumanize the delivery of medical care. In the US, a majority of the population (57%) believes that AI will significantly worsen the patient-provider relationship, because AI algorithms and automation cannot provide the empathy or compassion needed for healing. Medical and education experts warn of “automation bias,” where busy clinicians might blindly follow AI prompts rather than using their own critical judgment, potentially leading to a gradual de-skilling of the medical workforce.

#### 6. Lack of formal scientific testing

All advances in medical care have to undergo a prolonged process of formal scientific validation, including case-control studies, multiple randomized controlled trials (RCTs in Phase I, II, III), meta-analyses, and medical effectiveness testing before being incorporated into routine medical practice. Similar scientific validation rarely, if ever, occurs with incorporation of AI-based decision-making algorithms into medical care.<sup>9</sup> AI tools are being used to automate and streamline clinical trial operations throughout a randomized trial’s life cycle, including clinical trial design, identifying eligible patients, obtaining informed consent, selecting physiological and clinical outcomes, interpreting imaging, and analyzing or disseminating the results.<sup>10,11</sup>

In summary, although AI applications do have the potential to promote healthcare equity in several ways, key challenges remain in its deployment across different settings of care. First, AI can optimize resource utilization, improve public health surveillance, optimize workflow in hospitals and clinics, and improve overall efficiency, potentially benefiting underserved populations. Second, AI tools can identify the social determinants of health (SDoH) and target the limited resources to vulnerable populations, promoting greater fairness and health equity. Third, several AI solutions are claiming to provide personalized care by tailoring the treatments to achieve better individual outcomes.

However, in an unjust commercially-driven healthcare system, AI solutions may create tiers of care due to algorithmic bias and thus perpetuate or amplify existing racial and socioeconomic disparities in diagnosis, treatment, and resource allocation. Fairness and justice demand due considerations of patient need, efficiency, and discrimination in healthcare delivery. Wealthier nations, institutions and populations are likely to benefit more from cutting-edge AI, slowly widening the gap in care quality between the haves and have-nots, and eventually undermining equitable access, procedural justice, and accountability.

### Regulatory Responses

The regulatory responses to these rising concerns have been muted and fragmented. Launched in August 2024, the European Union has passed the world's first comprehensive AI law, categorizing most healthcare AI as "High-Risk". This law mandates that "high-risk" medical AI — including most diagnostic software and surgical robotics—must meet strict requirements for transparency, human oversight, and bias mitigation. The consequences of breaking this law are designed to be deterrent, whereby organizations that fail to comply face fines up to 7% of global annual turnover. To address the "liability gap" noted above, the EU has explicitly ruled to treat software as a "product", which makes it easier for patients to claim compensation for harm caused by defective AI, often shifting the burden of proof from the patient to the company if the AI's internal logic is too opaque ("black box"). To reduce demographic bias and health inequity, new EU rules from 2025 create a secure framework for researchers to access large, diverse datasets across the EU, specifically aimed at training AI models on more representative populations.

Instead of enacting a single overarching AI law, USA relies on the FDA's existing authority to regulate medical software. The FDA published a new framework in 2024, the Predetermined Change Control Plans (PCCP), allowing developers to pre-define how an AI model will "learn" and update after it is released.<sup>12</sup> This allows for continuous improvement while ensuring the FDA has already approved the method of change to prevent "algorithmic drift". Prior to that, President Biden had directed the Department of Health and Human Services (DHHS) to establish an AI Safety Program by creating a central repository to track clinical errors, discrimination, and bias incidents specifically caused by AI in healthcare.<sup>13,14</sup> Recent rules also require vendors of electronic health records (EHRs) to disclose greater details how their predictive algorithms were validated and will be monitored, giving clinicians better tools to detect potential errors in algorithmic logic.<sup>8</sup>

The collection, analysis, processing, and inferences from identifiable digital data for AI healthcare applications in India is covered by the Digital Personal Data Protection Act of 2023 (DPDPA). Healthcare AI tools like diagnostic models, clinical decision-support systems, chatbots, or telemedicine platforms must comply with the DPDPA when handling patient data. Patients must provide explicit and informed consent before their personal data can be processed by a healthcare AI application.<sup>15</sup> All healthcare providers including hospitals, clinics, digital platforms, and professionals are considered data fiduciaries under this Act. Technology vendors that process patient data on behalf of a healthcare facility are treated as data processors and their compliance with DPDPA is contractually obligated. However, the DPDPA does not categorize health data as specially "sensitive", which leads to weaker protections compared to EU standards. Further, it does not require explainability standards for AI, avoiding statutory mandates for the interpretation of AI decisions by patients or clinicians despite carrying consent and transparency obligations.<sup>15</sup>

For other countries that lack such rules, the World Health Organization (WHO) has issued 2024-2025 programmatic guidance specifically directed at Large Multimodal Models in healthcare. The WHO recommends mandatory post-release audits by third parties to verify that AI systems do not develop biased outcomes after acquiring real-world patient data. WHO also favors “human-in-the-loop” models, ensuring that critical medical decisions are not purely automated without a clear path for patients to challenge their rationale with the help of a human physician<sup>9</sup>. These are broad general principles and may not be legally binding, but they will certainly guide the developers of AI algorithms with some incentive to promote their products in low-resource populations.

With increasing penetration of AI healthcare applications into medical care, hospital and clinic operations, patient experience, health resource allocation, and other aspects, several concerns need to be addressed to enable widespread acceptance, safety, and equity of AI applications in healthcare. Patients are already experiencing the insidious direct and indirect effects of AI on their health and healthcare access. Experts in the field of healthcare and the developers of AI/ML technologies must collaborate to create human-in-the-loop applications formally test and validate all AI decision-making algorithms before they are incorporated into the clinical realm.

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Student Essay

## Indian Jews: A Case Study of Unique Religious Tolerance

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**Abstract:** This study explores the historical experiences of various and diverse Jewish communities in India, and investigates why they were largely spared from antisemitism, which Jews in Europe and the Middle East faced on a substantial level. Drawing upon a qualitative comparative case study, this study analyzes patterns of religious tolerance, social integration, and intercommunal relations across different regional contexts. This paper examines distinct Jewish communities in India and contrasts their varying experiences with Jews living in predominantly Christian and Muslim societies. This study argues that India's pluralistic religious environment, shaped by a distinct Hindu worldview the core principle of which can be summed up in the phrase 'Vasudaiva Kutumbakam,' which means the world is one family, played a crucial role in fostering a tolerant atmosphere. Indian Jews, before their emigration to Israel, Britain, Australia, and the United States, were well-integrated, respected, and protected by local rule, in contrast to the persecution and social exclusion Jews experienced elsewhere. Evidence from the Indian-Jewish experience offers what can be described as a counter-narrative to the global Jewish histories of antisemitism, and also demonstrates how structural, religious, and cultural conditions can shape coexistence.

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### Introduction

*“Antisemitism is a certain perception of Jews, which may be expressed as hatred toward Jews. Rhetorical and physical manifestations of antisemitism are directed toward Jewish or non-Jewish individuals and/or their property, toward Jewish community institutions and religious facilities.”*

International Holocaust Remembrance Alliance (IHRA), 26 May 2016<sup>1</sup>

The history of the Jews in India is ancient, with scholars dating the oldest communities to 562 B.C.<sup>2</sup> The Indian Jewish community, however, is exceptionally diverse, with new Jewish communities being established in India throughout its contemporary history. The main Jewish communities that settled in India over time include Cochin Jews, Madras Jews, Nagercoli Jews, the Jews of Goa, the Bene Israel Jews, the Bagdadhi Jews, the Bene Menashe Jews, the Bene Ephraim Jews, and eventually, European Jews fleeing persecution during World War II. In this study, I provide a historical overview of the different Jewish communities, their unique experiences in India, and explore the modern situation of Indian Jews.

The Cochin Jews are considered one of the oldest Jewish groups in India, claiming to be from the era of the biblical King Solomon<sup>3</sup> Ancient legend dates the first settlement of Jews in Cochin to the destruction of the First Temple in Jerusalem in 586 B.C., where some Jews were exiled, and subsequently made their way to India. The first physical records of Jews in Cochin date to 70 A.D., after the destruction of the Second Temple in Jerusalem, when Jewish settlers arrived in Cranganore, a port near Cochin.<sup>4</sup> The Jews of Cochin maintained a harmonious relationship with the local Indian rulers. The Jewish community in Cochin received a set of copper plates called “Sâsanam” granting them privileges such as self-rule and a portion of tax revenue.<sup>5</sup> Although the copper plates are physically inscribed with the date 379 A.D., they are thought to be from the early 11th century.<sup>6</sup> Regardless of its date, the copper plates serve as a physical testament to the amicable nature of the Indian-Jewish relationship in Cochin. Post 1947, when India became independent from Britain, and there was an emphasis on the partition of India, many Jews emigrated to Israel. The Indian Jews who emigrated still continue to speak Malayalam.<sup>7</sup> Several synagogues remain to this day and are preserved as historical sites.

Figure 1. A High Priest of the Cochin Jews.



Source: Wikimedia Commons (Public Domain).

Paradesi (literally meaning ‘foreign’ due to their late arrival to the Indian subcontinent) Jews are those who immigrated to India during the 15th and 16th centuries from Spain and Portugal after the expulsion of the Jews from Spain in 1492 by King Ferdinand II of Aragon and Queen Isabella I of Castille, and the expulsion of the Jews from Portugal in 1496 by King Manuel I. One place in India that the Paradesi Jews settled in was Madras, and the Paradesi Jews there subsequently became known as the Madras Jews. The Madras Jews specialized in trading Golconda diamonds (diamonds from mines in Golconda, India), other valuable stones, and corals.<sup>8</sup> Those Sephardic Jews included many from Amsterdam, who had fled the Spanish and Portuguese inquisitions earlier, but ultimately migrated to Madras. The Madras Jews, like the Cochin Jews, possessed good relations with the local Indian community and its government. While the history of the Paradesi Jews is less ancient than that of the Cochin Jews, it also serves as a demonstration of the special relationship between the Indian and Jewish communities.

Another group of Jews that migrated to India were the Nagercoil Jews, also known as the Musta’arabi (Musta’arabi, literally meaning “arabized” in both Arabic and Hebrew) Jews and the Syrian Jews. The Nagercoil Jews were Arab Jews who arrived in Nagercoil in 52 A.D. According to legend, the Nagercoil Jews arrived with St. Thomas or Thomas the Apostle, who traveled to India to preach the Gospel.<sup>9</sup> Like many other Jewish communities, the Nagercoil Jews were merchants, maintaining trade connections in Europe and throughout India. Their presence in Nagercoil was met with tolerance and no persecution; additionally, their language skills were useful to the local government. Compared to other Jewish groups in India, less is known about the Nagercoil Jews.

The Jews of Goa possess a similar history to the Paradesi Jews, with Spanish and Portuguese (Sephardic) Jews fleeing persecution from the Inquisition to Goa. While the Kingdom of Portugal established an Inquisition within its borders, it did not extend to its colonies until 1536. Many Sephardic Jews that settled in India became conversos, or New Christians, Jews who practiced Judaism in secret, but outwardly maintained Christian identities. In India, it was more difficult for the Inquisition to investigate them, make it a desirable place to both secretly practice Judaism, and maintain their professions as merchants in the Portuguese Empire.<sup>10</sup> Many Jews in Goa eventually made their way to other Jewish communities already established in India.

The Bene Israel community is perhaps one of the most complex Jewish groups in India, claiming to be descendants from the Ten Lost Tribes of Israel.<sup>11,12,13</sup> According to legend, the ancestors of the Bene Israel community are descended from fourteen Jews fleeing persecution from the Greeks in ancient Judea, who ended up in India after a shipwreck. When I visited the Bene Israel community in Mumbai and Alibag, I had the privilege of being shown a monument marking the place of the shipwreck that brought the Bene Israel to the Indian subcontinent. When they arrived, the Bene Israel took up the oil pressing trade, and did not work on the Sabbath, earning themselves the nickname “shanivar teli,” meaning “Saturday oil-presser.” Over time, the Bene Israel became integrated into the local Indian communities, while still preserving some Jewish customs, such as circumcision.<sup>3</sup> Since the Bene Israel Jews were highly integrated with the local Indian communities, they faced little discrimination in India. During my travels in India, I had the privilege of meeting Ralphy and Yaël Jhirad, Bene Israel Jews who currently live in Maharashtra. They expressed the struggles of not being recognized as “real Jews” by many various Jewish communities due to their history of being disconnected from the broader global Jewish community.

Figure 2. Photo of the monument marking the shipwreck where the Bene Israel landed in Alibag, State of Maharashtra, India.



The Baghdadi Jews, or Iraqi Jews, originating from mostly Baghdad, and other parts of the Middle East including Syria, Egypt, Yemen, Iran, and Turkey, began to settle in India (primarily in its port cities) in the 18th century.<sup>14,15,16,17</sup> The first Baghdadi merchant colony to be established in India was in Surat, in 1730. By the end of the 18th century, there were about 100 Baghdadi Jews living in Surat. In the early 19th century, there was an uptick in antisemitism in Mashhad, Iran and Aleppo, Syria, as well as an outbreak of plague in Baghdad, causing Jews from these communities to migrate to places like India. Eventually, the Baghdadi Jews spread to cities like Bombay and Calcutta, where there were more trade opportunities available. Before the onset of World War II, there were approximately 11,000 Baghdadi Jews in South Asia.<sup>14</sup> A few Baghdadi Jewish families, such as the Sassoon family, possessed great fortunes from their professions in trade; however, the overwhelming majority of Baghdadi Jews in India lived in poverty, resembling an oligarchic society. While the Baghdadi Jews in India were treated with tolerance by the local Indian communities, they faced discrimination from British rulers. Following the Partition of India and the ethnic tensions that emerged, many Jews immigrated to the newly established state of Israel, Australia, or Britain. Overall, the Baghdadi Jewish community viewed their experience in India positively, regarding the fact that they had never experienced antisemitism as a unique privilege.

The Bene Menashe Jews have a similar origin story to the Bene Israel Jews, also claiming to be descended from the Ten Lost Tribes of Israel; however, DNA testing does not support their claims (unlike the Bene Israel Jews, which possess Middle Eastern DNA). For centuries, they practiced a form of pseudo-Judaism, but for the most part, were unaware of most Jewish customs. In 2005, however, the Sephardic Chief Rabbi of Israel officially recognized the Bene Menashe as a lost tribe of Israel.<sup>18</sup>

An ethnographic study in Israel “among a community of immigrants from the Eastern Indian states of Manipur and Mizoram, Bene Menashe,” discusses “how these immigrants have used ethnic identity to further integrate into mainstream Jewish and Israeli society.”<sup>19</sup> The authors of the 2025 article in the *Asian Studies Review* note:

Originally known as the Kuki-Chin-Mizo, Bene Menashe claim to be descendants of the lost tribes of Israel, cut off from other Jews for 2,700 years. Several thousand members of the community have emigrated to Israel since the 1990s...Bene Menashe’s background as a singular community of East Asian immigrants in the peripheral town of KA and as recent converts to Judaism, as well as their Zomian (Upland Southeast Asian) background, are central to the community’s negotiation of ethnoreligious identity. Their efforts to integrate into contemporary Israeli society often contrast with the drive of Israeli cultural agents to emphasise the group’s lost tribal heritage, and the community has also both emphasised and sought to discard their previous ethnic identity.

A traditional harvest festival song called “Sikpui Ruoi” has been used to make the disputed claim that the Bene Menashe Jews are descended from the ancient Israelites.<sup>20,21</sup> “Sikpui Ruoi” lyrics are below:

While we are preparing for the Sikpui Feast,  
The big Red Sea becomes divided;  
As we march along fighting our foes,  
We are being led by pillar of cloud by day,  
And pillar of fire by night.  
Our enemies, O ye folks, are thick with fury,  
Come out with your shields and arrows.  
Fighting our enemies all day long,  
We march forward as cloud-fire goes before us.  
The enemies we fought all day long,  
The big sea swallowed them like wild beast.  
Collect the quails,  
And draw the water that springs out of the rock.<sup>20</sup>

Like the Bene Menashe Jews and the Bene Israel Jews, the Bene Ephraim Jews also claim to be descended from the lost tribes of Israel (instead of claiming to be descended from the biblical Menashe, they claim to be descended from the biblical Ephraim).<sup>21</sup> However, the Bene Ephraim Jews were never officially recognized as Jews by any official rabbinic bodies and cannot emigrate to Israel as a result.<sup>22,23</sup> The Bene Menashe Jews and Bene Ephraim Jews faced no antisemitism from the Indian community, partially due to their assimilation and integration into broader Indian society, and research on Andhra Pradesh demonstrates the importance of context.<sup>24,25,26</sup>

Despite the differences in India’s diverse landscape of Jewish communities, a common denominator is clearly present: the general lack of antisemitism and presence of religious tolerance. This common denominator of Jewish communities in India is unique to India: Jews faced antisemitism in both Europe and the Middle East (on a much higher scale in Europe) but not in India. In this paper, I explore the reason for India’s unique religious tolerance through a qualitative comparative case study of Jewish communal life in India, Europe, and the Middle East.

## Materials and Methods

This paper utilizes a qualitative comparative case study to investigate why Jewish communities in India experience little to no antisemitism, in contrast to Jews in Europe and the Middle East. The research for this paper incorporates historical records, academic literature, and field observations conducted during travel to India. The methodology for this paper includes a comparative historical analysis to identify patterns of religious tolerance and antisemitism across three contexts: India, Europe, and the Middle East. The dependent variable is the presence or absence of antisemitism, defined broadly to include legal restrictions, social discrimination, forced conversion, and violence. The independent variables include religious ideologies (Hinduism, Christianity, Islam), cultural norms, and Jewish integration vs. separation.

Each case (India, Europe, and the Middle East) is evaluated through the lens of these variables to assess the structural, social, and theological conditions shaping the experiences of various Jewish communities across the globe. Furthermore, this study treats the Indian Jewish community as a group of distinct communities (such as the Cochin Jews, Bene Israel, Baghdadi Jews, etc.) rather than as a monolith. The collective absence of antisemitism within so many diverse Jewish communities in India offers a unique counterpoint to other negative experiences that Jews faced in Europe and the Middle East.

## Results

This section addresses the central research question: Why have Jewish communities in India faced no antisemitism, compared to Jews in Europe and the Middle East who faced a considerable amount of antisemitism? A comparative analysis reveals that India's unique social, religious, and geopolitical conditions played a crucial role in fostering a more tolerant environment for Jews. Several factors account for India's tolerance of its diverse Jewish communities including its religious pluralism, geopolitical distance of India from Europe and the Middle East, a Hindu majority in India, and the integration of the Jews with the local Indian communities.

One of the most significant variables is India's diverse religious landscape and pluralism. India is known for being home to a multitude of religious minorities, including Muslims, Christians, Sikhs, Buddhists, Jains, Zoroastrians, and of course, Jews. Why have so many religious minorities been tolerated in India? Regardless of their various levels of conflict with the Hindu majority, the communities have been tolerated enough to remain, unlike other countries such as for example, Zoroastrians in the Middle East. Unlike Christianity or Islam, Hinduism is a non-proselytizing, non-monotheistic religion, and is not supersessionist. As a result, it lacks the historical framework for religiously motivated antisemitism.<sup>2,3</sup> In India, Jews were often viewed as one of many religious groups, rather than a unique anomaly, within a more inclusive general social fabric. The non-proselytizing nature of the Jewish religion also contributed to the absence of religious tension. Indian Jews didn't attempt to convert others to Judaism and were not perceived as religious competitors.

Another important variable to consider is the integration of the Indian Jews into the broader Indian social fabric and society, which occurred organically.<sup>27</sup> Unlike in Europe and the Middle East, Indian Jews often did not have their own quarters, villages, or neighborhoods, and lived and intermingled with their non-Jewish neighbors. A staple of Jewish life in Europe was the *shtetl*, small rural towns consisting of predominantly Jewish residents; a staple of Jewish life in the Middle East was separate Jewish quarters within cities, such as the *mellahs* in Morocco. The separation of Jews and non-Jews, historically, was both forced by and chosen by local rulers. However, in India, no such concept was prevalent. The Jews also adopted local languages and cultural aspects while still maintaining traditional Jewish customs. While Jews in the Middle East often adopted local languages, dress, and cultural aspects, their integration was not comparable to that of the Indian Jews; notably, the Bene Israel and more ancient Jewish communities in India. Furthermore, Middle Eastern Jews experienced

less antisemitism than European Jews, correlated with both levels of integration and religious environments. These two concepts taken together, provide evidence that suggests Indian Jews' lack of experienced antisemitism was due to India's pluralistic religious environment, cultural openness to minority groups, and non-dominance of Christianity or Islam.

### Conclusions

The experiences of Jewish communities in India stand out as a remarkable anomaly in the broader narrative of Jewish history and the Jewish Diaspora. Unlike in Europe or the Middle East, where Jews were often subjected to violence, exclusion, and systemic restrictions, India has offered a tolerant environment where Jews could thrive. Religious pluralism and the nature of Hinduism provided a theological foundation for tolerance in contrast to supersessionist ideologies embedded within Christian and Islamic societies. The social and economic integration of Indian Jews provided less separation than Middle Eastern and European Jews from broader non-Jewish society and allowed for more broader acceptance. India's pluralistic religious environment, shaped by an inclusive Hindu worldview the core principle of which can be summed up in the phrase 'Vasudaiva Kutumbakam,' which means the world is one family, played a crucial role in fostering a tolerant atmosphere.<sup>28</sup> Ultimately, the Indian Jewish experience offers a distinctive counter-narrative to dominant Jewish histories of persecution. Understanding the structural, cultural, and theological conditions that enabled Jews to thrive in India may serve scholars when thinking about society today.

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Article

## IXOHOXI Magic Square in Pādukā Sahasram by Sri Vedānta Deśika

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**Abstract:** Svāmī Srī Vedānta Deśika, an erudite Sri Vaiśnavite Acāryā is known for his mastery over creative formation of Sanskrit verses. He has exhibited his scholarly work in a number of verses of śrī Pādukā Sahasram. It contains verses praising the holy sandals of Srī Ranganātha. Several mathematical concepts are handled in this work. In addition, structural styles and symmetric beauty are also incorporated in ancient Sanskrit verses such as this. While these verses will flow to provide a meaning at the outset, the same verses are also arrived through certain patterns. This paper is an attempt to decode one verse from śrī Pādukā Sahasram and derive the format, structure and correlate these to known mathematical or structural style. To do that, the well-known Vedic Numerical Coding methodology is used, few mathematical concepts are analyzed and some known patterns are taken into consideration. In addition, Srinivasa Ramanujan's magic square pattern is also studied and compared to this verse.

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**Keywords:** Pādukā Sahasram, Srī Nigamānta Mahā Deśika, Vedic Numerical Code, Srinivasa Ramanujan's magic square, IXOHOXI magic square.

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### Introduction

Śrī Pādukā Sahasram) written by Srī Vedānta Deśika, occupies a unique place among Srī Vaiśnava Bhakti literature. He has written 1008 verses which exhibit not only his scholarly work in Sanskrit but also in mathematical concepts. This paper deals with one such verse adhering to the pattern of *ardhabhramakam*, IXOHOXI magic square and Srinivasa Ramanujan's magic square pattern.

**The Verse:**

The following verse from Śrī Pādūkā Sahasaram is taken for this study. It is verse number 933.

पापाद पापाद पापा पाद पाद दपा दपा ।  
 दपा दपा पाद पाद पाद पाद दपा दपा ॥  
 (pāpāda pāpāda pāpā pāda pāda dapā dapā  
 dapā dapā pāda pāda pāda pāda dapā dapā)

The brief meaning of the verse is as follows. The holy sandals of Śrī Ranganātha are free of sins and they store His grace as the rays in them. They bless the seekers and chase away their sins.

In the above verse only two letters are used and this can be shown in a picture and forms a geometric pattern. The verse actually is to be written along with its mirror image as shown below.

पापाद पापाद पापा पाद पाद दपा दपा ।  
 दपा दपा पाद पाद पाद पाद दपा दपा ॥  
 पाद पाद दपा दपा दपा दपा पाद पाद ।  
 पाद पाद दपा दपा पापाद पापाद पापा ॥

Following is the details about the numerical code used to decode this verse.

**Vedic Numerical Code कटपय सङ् (kaṭapaya saṅkhyā):**

In this numerical system

1. The Vyañjanam-consonants beginning with ka (क) and ta (ट) refer to digits from 1 to 9 (i.e. letters from ka (क) to jha (झ) and from ta (ट) to dha (ध) denote 1 to 9.
2. Pa (प) to ma (म) stand for 1 to 5.
3. Letters from ya (य) and ha (ह) represent the digits 1 to 8.
4. The nasal letters nya (ञ) and na (न) denote 0.
5. In the case of conjunct consonants, the number denoted only by the last consonant is taken into consideration.
6. The vowels following consonants have no value.
7. The vowels not preceded by any consonant represent 0.
8. The arrangement of the digits is from right to left as per the rule अङ्कानाम् वामतो गतिः (aṅkānām vāmato gatiḥ:)
9. The letter la (ळ) peculiar to the Dravidian languages represent 9.
10. The letter ksha (क्ष) denotes 0

## Assignment Table

1	2	3	4	5	6	7	8	9	0
क	ख	ग	घ	ङ	च	छ	ज	झ	ञ
ट	ठ	ड	ढ	ण	त	थ	द	ध	न
प	फ	ब	भ	म					
य	र	ल	व	श	ष	स	ह	ळ	&f
ka	kha	ga	gha	ṅa	ca	cha	ja	jha	jña
ta	tha	da	dha	na	ta	tha	da	dha	na
pa	pha	ba	bha	ma					
ya	ra	la	va	śa	sa	sa	ha	la	ksa

Katapaya Sankhya rule is as follows.

कादि नव टादि नव पादि पञ्च याद्यष्टौ।  
kādi nava ṭādi nava pādi pañca yādyaṣṭau |

1. कादि नव means ka and the following 8 letters ranging from digits 1 to 9.
2. टादि नव means ta and the following 8 letters ranging from digits 1 to 9.
3. पादि पञ्च means pa and the following 4 letters ranging from digits 1 to 5.
4. याद्यष्टौ means ya and the following 7 letters ranging from digits 1 to 8.
5. Ksha is equal to 0.

Using the above rule the table shown below is formed for the verse in discussion with digit “1” representing “पा” and digit “8” representing “द”.

1	1	8	1	1	8	1	1
1	8	1	8	8	1	8	1
8	1	8	1	1	8	1	8
1	8	1	8	8	1	8	1
1	8	1	8	8	1	8	1
8	1	8	1	1	8	1	8
1	8	1	8	8	1	8	1
1	1	8	1	1	8	1	1

Figure 1

**The findings:**

From the above 8 x 8 square, one can identify all combinations of digits 1 & 8 and form sixteen 4-digit numbers as follows.

1111 1811 8111 8811

1118 1818 8118 8818

1181 1881 8181 8881

1188 1888 8188 8888

By scanning the numbers horizontally in picture 1, following eight 4-digit numbers are identified.

1181, 1811, 8118, 1818, 8188, 1881, 8818 and 8181.

1	1	8	1	1	8	1	1
1	8	1	8	8	1	8	1
8	1	8	1	1	8	1	8
1	8	1	8	8	1	8	1
1	8	1	8	8	1	8	1
8	1	8	1	1	8	1	8
1	8	1	8	8	1	8	1
1	1	8	1	1	8	1	1

Figure 2

Scanning diagonally, we get the following eight 4-digit numbers.

1111, 1888, 8881, 8811, 1188, 1118, 8111 and 8888

1	1	8	1	1	8	1	1
1	8	1	8	8	1	8	1
8	1	8	1	1	8	1	8
1	8	1	8	8	1	8	1
1	8	1	8	8	1	8	1
8	1	8	1	1	8	1	8
1	8	1	8	8	1	8	1
1	1	8	1	1	8	1	1

Figure 3

By rearranging all the sixteen 4-digit numbers in a square we get the following table which reveals several mathematical facts bundled inside this beautiful verse in Śrī Pādukā Sahasram.

## Result

### a. IXOHOXI magic square

8818	1111	8188	1881
8181	1888	8811	1118
1811	8118	1181	8888
1188	8881	1818	8111

Figure 4

Picture 4 shows how these sixteen numbers form the IXOHOXI magic square. In this magic square total of all numbers in each row, column, diagonal will be 19998.

### b. Ramanujan's magic square pattern

8818	1111	8188	1881
8181	1888	8811	1118
1811	8118	1181	8888
1188	8881	1818	8111

Figure 5

Picture 5 shows just 5 combinations where same total is obtained. In addition to the summation of 4 numbers as shown above, the same total is obtained in the following combinations as well.

1. Four corner numbers.
2. 4 numbers in second and third row of first two columns and 4 numbers from right two columns of same rows
3. 4 numbers from top and bottom rows of middle two columns and 4 numbers of middle two rows of first and last column.

All these above are showing that the verse follows the pattern of Ramanujan's magic square.

c. अध मकम् (ardhabhramakam)

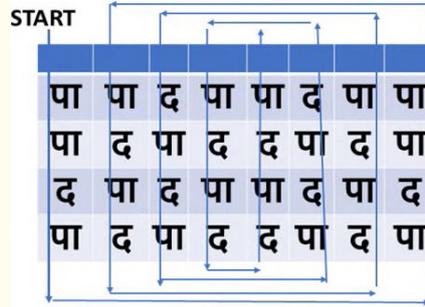


Figure 6

Svāmī Srī Vedānta Deśika, embeds this formation in many of his verses where one can start from top left and go around counter clockwise as shown above and the same verse is formed.

d. Symmetry

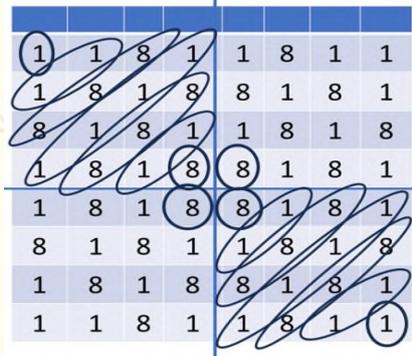


Figure 7

The verse encoded as shown in Picture 2 also forms a beautiful symmetric structure which is shown in Picture 7. The third quadrant is a mirror image of first quadrant and second quadrant is a mirror image of fourth quadrant. Picture 7 shows such a symmetry in quadrants 2 and 4 as an example.

**Conclusion**

Svāmī Srī Vedānta Deśika is a multi-faceted genius who was described as a Lion among Poets and Logicians, किव-तिका क-के सरी (Kavi-Tārkika-Kesarī) and a Sarva-Tantra- Svatantra. This paper shows only one aspect taking an example of just one verse from śrī Pādukā Sahasram.

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Narrative Review

## Advancements and Challenges in AlGaIn and Phosphor-Based Deep Ultraviolet LEDs: Towards Broader Applications and Higher Efficiencies

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**Abstract:** Recent progress in deep ultraviolet light-emitting diodes (DUV LEDs) has revolutionized applications in sterilization, water purification, and biomedical imaging. Their effectiveness in viral and bacterial inactivation, notably demonstrated during the COVID-19 pandemic, underscores their critical role in public health and environmental safety. DUV light sources offer mercury-free operation, compactness, and wavelength tunability, positioning them as sustainable alternatives to traditional mercury lamps. Over the past decade, significant advances in substrate engineering, optimized epitaxial growth of AlGaIn layers, and the discovery of efficient inorganic phosphor materials have enhanced device performance, with reported wall-plug efficiencies improving from below 1% to over 8% for AlGaIn-based LEDs operating in the 250–280 nm range. The present review provides overview on the recent progress, advancements and existing challenges in AlGaIn and other inorganic phosphor based DUV LEDs, focusing on efficiency device design strategies and overall lifetime. Despite these achievements, challenges such as limited external quantum efficiency (typically below 10%), high threading dislocation densities, and inefficient light extraction remain major issues to be resolved. Recent strategies like nanostructured quantum wells, polarization engineering, advanced reflective electrodes, hybrid AlGaIn phosphor architectures and nano-patterned sapphire substrates, combined with optimized doping, thermal management, and quantum barrier engineering, have significantly enhanced DUV LED efficiency, stability, and reliability. Looking forward, future research is expected to focus on integrating advanced nanofabrication techniques, improving thermal management, and developing cost-effective large-area substrates to achieve high-efficiency, scalable DUV LED systems suitable for next-generation photonic, environmental, and biomedical applications.

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**Keywords:** Deep Ultraviolet LEDs (DUV LEDs), Semiconductors, Phosphor Materials, Sterilization and Biomedical Applications, External Quantum Efficiency (EQE)

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## I. Introduction

The genesis of DUV technology finds its origin tracing to the conventional mercury lamp sources, and eventually evolved with the discovery of wide band-gap semiconductors. Based on their emission wavelength, UV LEDs have proved to support wider range of applications. UV emission is classified into three bands: UV-A (400 nm – 315 nm), UV-B (315 nm – 280 nm) and UV-C (280 nm – 200 nm).<sup>1</sup> UV-A and UV-B LEDs initiate the process of polymerization reactions in industrial processes such as coatings, adhesives, inks and 3D printing.<sup>2</sup> Apart from displaying greater energy efficiencies, the main reason that led to the development of DUV LEDs is their efficacy against the chlorine resistant pathogens such as cryptosporidium, which proved to cause numerous gastro-intestinal illnesses.<sup>3</sup> DUV LED is a well-known suitable light emitter in the UV-C spectrum (280 nm to 200 nm).<sup>4</sup> When emitted in this wavelength range, these LEDs find application, primarily for sterilisation of microbes, water purification, curing etc.<sup>5,6</sup>

The commonly used traditional UV light sources such as mercury vapour lamps generally pose environmental hazards, due to the stated toxic nature of mercury.<sup>7</sup> Additionally, poor energy efficiencies of mercury lamps guided researchers for developing novel DUV LED materials, that are toxic free.<sup>8,9</sup> The Minamata Convention in 2013 further enhanced the development of mercury free alternative materials, thereby placing DUV LEDs as a sustainable solution.<sup>10</sup> The main reason of preferring UV LEDs over mercury lamps is due to their efficiency, compactness and environmental safety.<sup>6</sup>

Traditional water treatment methods like filtration and dependence on chlorine show almost no effect in neutralizing the microbes.<sup>11</sup> UV-C LEDs, when emitted in DUV region, are extremely effective for inactivation of viruses, bacteria and spores by inducing photochemical changes (disrupt the DNA/RNA replication) in their nucleic acids. Kim et al.<sup>12</sup> have reported that a dose of 40 mJ/cm<sup>2</sup> is just enough for neutralizing most of the microbes and pathogens, making these suitable for water purification and surface disinfection for household portable systems<sup>13</sup>. Similarly, Stanley's electric DUV LED material emitting 265 nm at 40mW output, had shown 99.9% inactivation rate for the bacteria E.Coli, within 120 seconds.<sup>8</sup> Such parameters were to be adopted in healthcare disinfectant systems, water purification and sterilisation. Researchers have developed several organic and inorganic based DUV light emitting materials for obtaining greater efficiencies.

III-V and IV-VI compound semiconductors / insulators are distinguished by their ultra-wide band-gaps, that enable higher optical transparencies and efficient operation in DUV spectral region.<sup>14</sup> DUV LEDs which are based on group-III nitrides and inorganic phosphors offer compact form factors, operate at moderate direct currents, exhibit longer operational lifetimes, environmentally friendly and provide tunable emission wavelengths through the compositional engineering of active materials. This intrinsic property makes them ideal in the field of solar-blind photodetectors and other notable DUV sensing technologies<sup>15</sup>. Strong structures give these materials high thermal and chemical stability, thereby enabling a consistent performance under extreme conditions and intense DUV irradiation. Adding to their stability factor, these compounds also exhibit distinct nonlinear optical behaviours, such as strong 2<sup>nd</sup> harmonic generation and phase matching capabilities, that are essential in efficient frequency conversion for photonic DUV systems.<sup>16-18</sup> Additionally, the environmental compatibility and ease of high-quality crystal growth further enhance their suitability for scalable and sustainable integration into next-generation DUV optoelectronic systems devices.

The detailed comprehensive analysis of the efficiency between conventional mercury lamps and DUV LEDs is presented below:

- **Spectrum analysis**

Conventional mercury lamps emit broad UV spectrum, which disables deeper curing penetration and involves toxic mercury and ozone generation. DUV LEDs emit narrowband wavelengths (typically 255nm to 280 nm for AlGaIn LEDs) with no toxic materials, enabling environmental benefits and deeper penetration.<sup>19</sup>

- **Lifetime**

Traditional Mercury lamps have a relatively shorter operational lifetimes, typically around 1,000 to 12,000 hours, depending on the pressure and lamp type, with medium-pressure lamps usually lasting less than the low-pressure lamps.<sup>20</sup> DUV LEDs offer much longer lifetimes, typically up to 50,000 to 100,000 hours for certain devices.<sup>21</sup> This implies fewer replacements of these bulbs and lower maintenance costs. LEDs operate without warmup or cooldown periods, whereas mercury lamps require warmup time, and these degrade progressively with more usage.

- **Energy Efficiency**

The conventional mercury lamps have a typical wall-plug efficiency (WPE), ranging from 10% to 40%, depending on the lamp type (whether low type, or medium type, or pressure type) and application, with emissions mainly centered around 254 nm.<sup>22,23</sup> DUV LEDs currently have a WPE around 1% to 3%, but the ongoing technological advances expect to increase this beyond 10% in the future.<sup>10</sup> LEDs consume significantly less power than mercury lamps, contributing to lower operational costs and better energy conservation.

In addition, few advantages of III-V and IV-VI materials are summarized in the tabular column below.

Table I Advantages of III-V and IV-VI materials

Merit	Description	Reference
Wide Bandgap & DUV Transparency	Enables DUV emission and solar-blind detection	[24]
Chemical & Thermal Stability	Ensures reliability of the device in harsher environments	[25]
High Sensitivity & Swift Response	Provides ultrafast and selective DUV detection	[26]
Enhanced Nonlinear Optical Properties	Enables efficient DUV frequency conversion	[27]
Environmentally Friendly & Crystal Growth	Assists in scalable fabrication and eco-friendly material design	[28]

## 2. Synthesis of DUV LEDs using substrate engineering and epitaxial growth

A milestone in GaN technology in the late 1980s gave rise to blue LEDs, which enabled the production of efficient artificial white light LEDs.<sup>29</sup> Gallium, when alloyed to AlN gives AlGaIn based LED materials, which typically emit in UV range giving rise to several notable applications.<sup>30</sup> The synthesis of high performance DUV LEDs mainly depends on minimizing the crystalline defects present in the AlGaIn layers, which directly have an impact on their Internal Quantum Efficiency

(IQE). The dislocation density parameter, with its value lesser than  $2 \times 10^8 \text{ cm}^{-3}$ , is crucial in minimizing the non-radiative recombination. AlN substrates typically have low lattice mismatch as compared to AlGaIn and have become the basis for DUV LED fabrication.

Before we further proceed on discussion on several advancements in substrate engineering, it is essential to understand that the main degradation mechanism in DUV LEDs mainly emerges from defect related non radiative recombination, thermally induced nonuniform composition and leakage current led optical losses.<sup>31</sup> The main factors that significantly minimize EQE and device reliability can be stated as point-defects, Al ion migration and Shockley-Read-Hall recombination under thermal and electrical stress.<sup>32</sup> Several notable effects such as advanced thermal management designs, carefully modified silicone / ceramic packing and graded AlGaIn superlattice structures have been developed by researchers to mitigate the previously stated factors. These processes not only prevent leakage, improve heat dissipation and reduce defect densities, but also help in achieving greater device stabilities and longer device lifetimes.

Recent advancements in engineering the substrate for AlN had shown an enhancement in the power output of DUV LEDs. A pseudo 2D growth of good quality AlN films on graphene substrate had a reduced effect on the dislocation density and strain, thus achieving a remarkable 22% increase in the output power for 272 nm devices, which was achieved through improved IQE and light extraction efficiency (LEE).<sup>33</sup> Choosing sapphire over AlN substrates had minimized the lattice mismatch, thus giving a 100-fold power enhancement for 280 nm DUV LEDs, through enhancing the carrier injection efficiency.<sup>34</sup> Further optimization of the AlN crystal plane orientation had shown benefits of anisotropic light extraction, thus boosting the emission intensity of 210 nm LEDs, which was achieved through the minimization of photon losses at specific crystallographic interfaces.<sup>35</sup> In addition, high-temperature annealing of hydride vapor phase epitaxy (HVPE) grown AlN substrates had demonstrated an improvement in the surface morphology, thus enhancing LEE by 8% for 265 nm flip-chip LEDs, achieved through reduced interfacial roughness.<sup>36</sup> The stated innovations collectively report the critical role of the quality of substrate, via graphene integration, lattice matching, crystallographic tuning, and post-growth processing, for advancing DUV LED performance in applications for disinfection, spectroscopy, sensing etc. Between 2013 and 2023, the power output exhibited by DUV LEDs ranged between 10 mW to 200 mW, which was mainly due to the result of the enhancement of the AlN substrate quality.<sup>13</sup>

It is crucial to acknowledge that substrate engineering is a key factor in improving the internal and external quantum efficiencies of AlGaIn-based DUV-LEDs, mainly achieved by optimizing the Aluminium composition within the active and buffer layers. Results from recent research studies show that growth on AlN substrates drastically reduces the threading dislocation density, that is very much crucial for achieving high IQE in Al-Rich AlGaIn layers.<sup>37</sup> This results in improvement up to one order of magnitude compared to the conventional sapphire substrate. Though Sapphire is cost-effective, it results in significant lattice mismatch, thereby lowering IQE in DUV compositions due to enhanced defect densities.<sup>38</sup> In addition, the refining of the surface and advanced photonic structures on the substrates contribute to greater values of EQE, through promoting better light extraction. Thus, advanced substrate engineering techniques directly address, not only the crystal quality and optical management, but also deliver marked quantum efficiency gains throughout the composition range of AlGaIn.

Amongst various synthesis methods of DUV materials, epitaxial growth is a unique method preferred, as it offers precise control on the crystallinity of the material, thickness of the layers and interface quality. These factors are crucial and important for the performance of DUV materials. DUV carbon materials like carbon nanostructures and wide band-gap graphene, are emerging as key components in high-performance optoelectronics, photodetectors, and next-generation quantum devices.

A promising approach involves the epitaxial growth of graphene on silicon carbide (SiC). In this technique, SiC is heated to elevated temperatures under ultra-high vacuum conditions, leading to the sublimation of silicon atoms. The remaining carbon atoms then re-organize into well-ordered graphene layers on the SiC substrate. Though this method results in graphene with excellent structural and electronic properties, attaining uniformity in larger area and maintaining consistent layer thickness is a significant hurdle for scalable DUV applications. However, this limitation is overcome by another innovative technique known as remote epitaxy, which involves growing crystalline films on a substrate that is coated with 2D material such as graphene.<sup>39</sup> Another promising epitaxy strategy is known as the Van der Waals epitaxy, that relies on weak interlayer forces between the substrate and the deposited film, and is most ideal for integration in DUV systems.<sup>40</sup> Recent studies have also reported the epitaxial growth of carbon nano-fibres using carbon nanotubes, through the deposition of pyrolytic carbon in the gaseous phase, followed by high-temperature annealing.<sup>41</sup> Using this method, researchers have produced nanofibers with excellent thermal and mechanical flexibility, suited for extreme DUV environments.<sup>41</sup> Further film quality and reproducibility can be enhanced through substrate surface engineering techniques like application of buffer layers, surface coatings, or chemical treatments. These techniques help in minimizing defects, control the film thickness and improve the homogeneity of epitaxial layers, which are crucial for consistent DUV device fabrication.<sup>42</sup> Future efforts must focus on refining the epitaxial control through exploration of novel substrates and incorporation of real-time growth monitoring of the DUV carbon materials.

### 3. Thermal management techniques for high power DUV LEDs

High-power operations typically generate significant heat at the junctions, leading to reduced LED lifetime; hence, efficient thermal management is essential. To address this issue, thermal-based heat sinks are commonly employed, while the mercury-free design of DUV LEDs further supports sustainable development goals. Efficient thermal management in high-power DUV LEDs largely depends on advancements in both material selection and packaging design, which help lower the junction temperature and improve device reliability.<sup>43</sup> Ceramic substrates such as Aluminium nitride (AlN) offer high thermal conductivity and enable dense packing, making them highly suitable for efficient heat dissipation in DUV applications.<sup>44</sup> However, their relatively high cost compared to Aluminium or Aluminium-based ceramics limits their widespread use. To further enhance heat dissipation and spreading, standard industrial techniques such as thermal arrays, copper planes, and active cooling methods (including liquid cooling and forced convection) are employed.<sup>45</sup> Moreover, microchannel cooling structures and phase-change materials have gained considerable attention for mitigating thermal gradients and localized hotspots in compact, high-power device configurations.<sup>46</sup> Overall, substantial progress has been achieved over the past few decades through the integration of high-thermal-conductivity ceramic materials with advanced cooling structures, resulting in enhanced thermal management at both the device and system levels.

### 4. Wavelength conversion using phosphor materials

Though phosphors are essential ingredients in development of visible LEDs, they also play a crucial and important role in DUV LEDs. Band-gap engineering in GaN is essential to achieve excellent optoelectronic properties for applications in lasers, LEDs and several high-power devices. Thus, bandgap engineering in AlGaIn-based deep ultraviolet (DUV) materials enables tunable emission from 200-280 nm by systematically varying aluminium composition from GaN (3.4 eV) to AlN (6.2 eV).<sup>47</sup>

Techniques like strain-engineering have reported a compressive strain in GaN/AlGaN nanowires, that can induce band-gap shifts up to 240 meV.<sup>48</sup> Similarly, it was reported that uniaxial strain of GaN nanowires leads to a linear decline of the band-gap.<sup>49</sup> Several doping and co-doping strategies like co-introduction of C-Ge or C-Sn create meta-stable states, which narrow the band-gap and enhance the visible light absorption.<sup>50</sup> The phenomenon of Quantum confinement observed in GaN nanostructures has also shown an increase in the band-gap with reduced size due to surface effects.<sup>51</sup> These reported strategies have collectively enabled precise control over GaN band structure for DUV device applications.

#### 4.1 GaN based DUV LEDs

Yi Lu et al.<sup>52</sup> reported monolithic integration of DUV and visible LEDs for the radiative sterilization applications. This was accomplished by cascading AlGaN/AlGaN/AlGaN multiple QWs and GaN/InGaN/AlGaN QWs through the compositional grading AlGaN cascade region, as shown in figure 1.

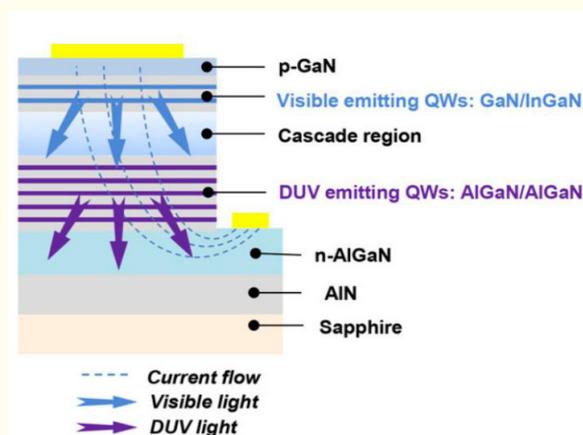


Figure 1 Schematic structure of the proposed LED, containing visible emitting QWs grown on top of the DUV emitting QWs.

The inevitable overflow electrons from DUV QWs are deliberately introduced into the visible QWs, allowing for the electron–hole recombination and the simultaneous emission of visible light. Both experiment and simulation results confirmed the feasibility of the proposed dual-wavelength LED integration. The proposed DUV & visible LED showed an EQE and WPE of 2.03% and 1.54% at 40 mA, respectively.

Ke Jiang et al.<sup>53</sup> fabricated AlGaN-based DUV LEDs with different wavelength on high-temperature-annealed (HTA) AlN/Sapphire templates. The AlN/AlGaN superlattices were employed between the template and upper n-AlGaN to release the strong compressive stress (SCS), improving the crystal quality and interface roughness. DUV LEDs with the wavelength of 256, 265, and 278 nm, corresponding to the light output power of 6.8, 9.6, and 12.5 mW, were realized. They argued that GaN/AlN QWs possess strong quantum confinement in one-monolayer limit which dramatically enhances the exciton binding energy (up to 230 meV). This provides extreme 2D confinement of excitons, being ideally suited for light generation in the deep ultraviolet. Toropov et al.<sup>54</sup> have reported a single monolayer of GaN in AlN as a heterostructure fabricated by molecular beam epitaxy<sup>55</sup> which provides extreme 2D confinement of excitons, which is ideal for light generation in the DUV region. They have also reported an internal quantum yield of 75% at room-temperature, due to excitonic emission at 235 nm. Lu et al.<sup>56</sup> demonstrated a truncated pyramid nanostructure in (AlN)<sub>8</sub>/(GaN)<sub>2</sub> digital alloys, fabricated using nanoimprint lithography and etching techniques. They further stated that the design enhanced LEE by 191%, compared to planar structures, as shown in figure 2.

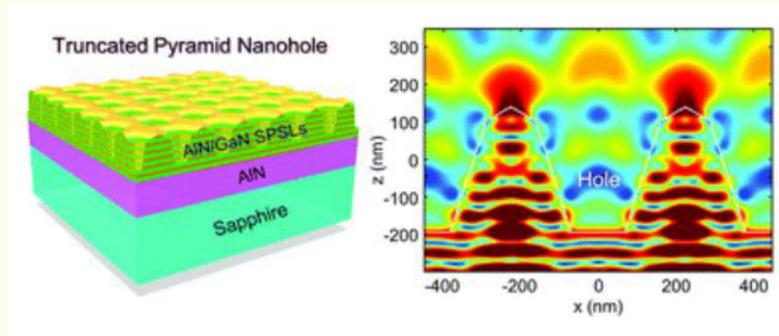


Figure 2 Truncated pyramid nanostructure of AlGaIn DUVs

Chenguang He et al.<sup>57</sup> achieved self-organized high crystalline quality of AlGaIn quantum wire arrays, by engineering the surface morphology of AlN templates, that resulted in IQE of 70% for DUV emission.

### 4.2 Band gap engineering in AlGaIn based DUV LEDs

The energy band gap of  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  alloys increases steadily as more Aluminium is added from about 3.4 eV in pure GaN ( $x = 0$ ) to about 6.2 eV in pure AlN ( $x = 1$ ). This change in composition lets us adjust the light emission wavelength from 365 nm (near-ultraviolet) to 210 nm (deep ultraviolet), which is useful for things like killing germs, cleaning water, and detecting chemicals. The increase in band gap happens because the conduction band moves up and the valence band moves down as Aluminium content rises as illustrated in figure 3. This shift makes the emitted photons more energetic, producing shorter wavelengths. In LED devices made from AlGaIn, the light-emitting region called the multiple quanta well can be designed with specific Aluminium levels to control the colour of light. This idea, known as “Emission Tunability via Al Content Engineering” is key to making advanced deep-UV light sources. Experiments and computer models show that the band gap doesn’t change in a straight line, it bends slightly, which scientists describe using the Varshni equation and a bowing factor.

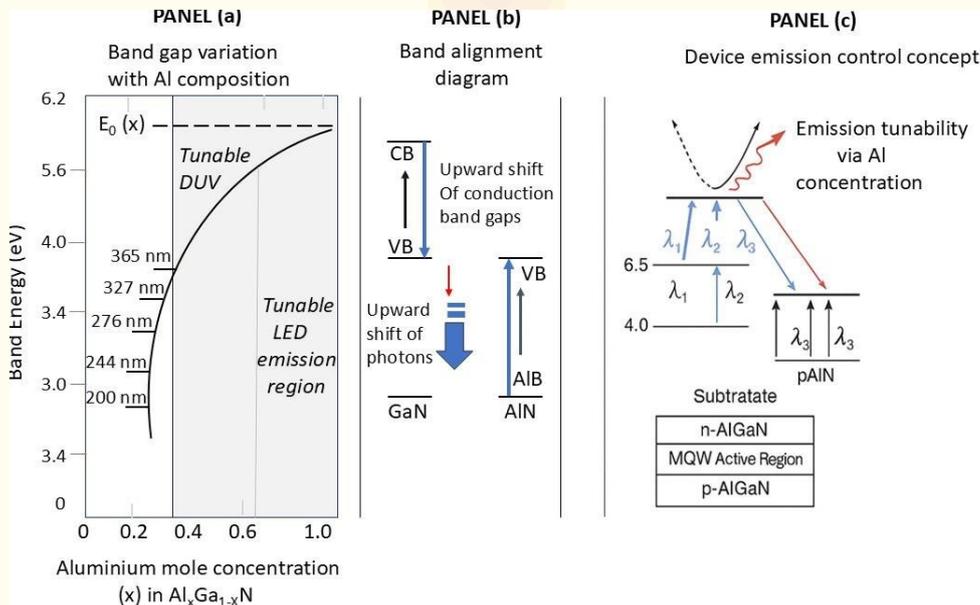


Figure 3: (a) Band-gap energy ( $E_g$ ) increases smoothly from ~3.4 eV (GaN) to ~6.2 eV (AlN) as a function of Al mole fraction ( $x$ ). Emission wavelength with band gaps 365 to 210 nm are shaded highlighting the tunable DUV emission window (range: 200 to 300 nm). (b) Band alignment for GaN, AlGaIn and AlN illustrating conduction band upward shifts and valence band downward shifts with increasing Al content, Arrows show electric transitions of DUV photons with varying energy ( $\lambda_1, \lambda_2, \lambda_3$ ). (c) AlGaIn based LED structure emphasizing emission tunability via Al composition in multi-quantum well layers.

### 4.3 Research Gap in AlGaN and Phosphor-Based DUV LEDs

AlGaN-based DUV LEDs face inherent challenges such as low hole injection efficiency and UV absorption in p-layers. Recent advancements, including nanoscale structuring, reflective contact design, substrate engineering, and the incorporation of molecular p-type dopants such as DPI-TPFB and F4TCNQ to enhance hole mobility and reduce injection barriers.<sup>58</sup> Strategies for interfacial engineering such as energy-level tuning of hole transport layers and valence state optimization via UV zone treatment have collectively led to significant improvements in charge balance and defect reduction.<sup>59</sup> Up to fourfold enhancements in EQE and device lifetime in blue PeLEDs and solution-processed QLEDs advance the overall reliability and performance of optoelectronic devices.

The maximum efficiency reported for DUV LEDs varied across different studies, with significant advancements in recent years. The highest EQE achieved reported was 11% for 278 nm AlGaN based DUV LEDs, due to the improvement in material quality and light extraction techniques.<sup>60</sup> Such lower values of EQE generally limits the antibacterial and sterilization effectiveness. Other notable efficiencies include 7.2% for a 255 nm tunnel junction LED, which represents a substantial increase over previous designs.<sup>61</sup> Additionally, a 254 nm tunnel junction LED demonstrated an IQE of approximately 88%, marking a significant milestone in DUV LED technology.<sup>62</sup> The typical challenges of these include higher threading dislocation densities due to lattice mismatch with substrates, low light extraction efficiency (LEE), and carrier injection issues reducing IQE.<sup>63</sup> To combat these issues, packaging of these LEDs, device reliability, efficiency improvement in hole injection, control of electron leakage and optical extraction are the active research avenues for the researchers. The main reason in using of AlGaN based DUV LEDs lies in raising the WPE parameter and stable outputs comparable to the mercury lamps, to enable broader industrial and biomedical applications.

### 4.4 Inorganic Phosphors / Nanophosphors based DUV LEDs

Phosphate-based phosphors, such as Bi doped yttrium phosphate ( $\text{YPO}_4$ ), Pr activated  $\text{Ca}_2\text{Al}_2\text{SiO}_7$ , and  $\text{Pr}^{3+}$ -doped  $\text{Li}(\text{Al}_7\text{B}_4\text{O}_{17})$  have proved to be a potential material for tunable emission spectra.<sup>47-49</sup> When activated by Bi or Pr, these inorganic phosphors emit DUV-C light under UV excitation, thus offering methods for development of multifunctional DUV devices, for potential applications for both illumination and disinfection.<sup>50</sup> However, phosphors based DUVs require excellent stability when irradiated with higher energies, which is an area of further research. Xu et al.<sup>64</sup> have stated in their work the unique features in the atomic and electronic configurations of DUV light emitters. They have reported the fundamental genetic reasons as to why DUV light emitters are extremely rare. They have studied the design and synthesis of several DUV light emitters and established the genetic nature of ultrawide band-gap semiconductors. They have also worked and arrived at a high-throughput computational search for DUV light emitters, based on specially designed screening criteria relating to electronic structure. Through this approach, they have identified 5 promising material candidates that exhibit comparable or higher radiative recombination coefficients than AlN, like  $\text{BeGeN}_2$ ,  $\text{Mg}_3\text{NF}_3$ ,  $\text{KCaBr}_3$ ,  $\text{KHS}$ , and  $\text{RbHS}$ . Lin et al.<sup>65</sup> reported  $\beta\text{-Ga}_2\text{O}_3$  p-i-n heterostructure grown on p-GaN by sequential vapor-cooling condensation of i- $\text{Ga}_2\text{O}_3$  and Si-doped  $\text{Ga}_2\text{O}_3$ , followed by 900°C annealing. The device showed strong deep-UV electroluminescence peaking at 248 nm. They have also measured and reported the electron concentrations to be  $\sim 1 \times 10^{15} \text{ cm}^{-3}$  in i- $\text{Ga}_2\text{O}_3$  and  $2.2 \times 10^{17} \text{ cm}^{-3}$  in n- $\text{Ga}_2\text{O}_3\text{:Si}$ . Mohammad M. Afandi et al.<sup>66</sup> have also reported DUV electroluminescent device using  $\text{Bi}^{3+}$  doped yttrium phosphate (YBP) phosphor. They have optimized dopant concentration, phase-morphological, and electro-optical properties of the developed YBP phosphor. They also reported that under AC-driven sinusoidal waveform, the EL emits a narrowband DUV spectrum peaking at 243 nm. Rojas-Hernandez et al.<sup>67</sup> reported in their work that undoped

ZnAl<sub>2</sub>O<sub>4</sub> fibers which were synthesized through cost-efficient wet chemical route. The rare-earth-free ZnAl<sub>2</sub>O<sub>4</sub> nanofibers exhibited a strong UV emission with two bands, peaking at 5.4 eV (230 nm) and 4.75 eV (261 nm) respectively. The emission intensity was controlled through tuning the Zn/Al ratio. Xulong Lv et al.<sup>68</sup> synthesized ScBO<sub>3</sub>:Bi<sup>3+</sup> phosphors via a high-temperature solid-state reaction method. These phosphors exhibit intense and long-lasting DUV-C luminescence centred at 299nm due to the presence of various defect levels and external stimulus, which show excellent energy storage capabilities. Yan-Min Yang et al.<sup>69</sup> developed Pr-doped polycrystalline fluoride lepidolite persistent phosphors (Cs<sub>2</sub>NaYF<sub>6</sub>:Pr<sup>3+</sup>) which was prepared by high temperature solid-state reaction method. This phosphor showed strong UV-C emission at 250 nm, with an initial power density over 10 mW/m<sup>2</sup> and an afterglow greater than 2 hours. Wang et al.<sup>70</sup> reported Pr<sup>3+</sup> doped Li(Al<sub>7</sub>B<sub>4</sub>O<sub>17</sub>) nanocrystals (NCs), embedded with fluoride in the glass matrix. These nano-GCs reported DUV emission at 250 nm, with the photoluminescence quantum yield of 25.93%.

DUV LEDs have emerged as a green and sustainable alternative to conventional mercury-based lamps, particularly for applications such as disinfection and sterilization. This transition has sparked significant research interest, aimed at enhancing the performance and efficiency of DUV LED devices. Amongst them, AlGaIn-based DUV LEDs have gathered particular attention, as researchers strive to address persistent challenges related to reliability, efficiency, and thermal management. For example, Li et al. have reviewed AlGaIn DUV LEDs and reported that these materials typically have EQEs below 10%, due to polarization fields and poor p-type doping.<sup>55</sup> Selective promising techniques such as thermal annealing of reflective electrodes<sup>38,71</sup> have shown promise, by offering significant gain in the EQE. Researchers have also relied on several computational screening methods for identifying potential DUV light emitters with desirable properties.

Progress in UV-C emitting phosphors and study of nonlinear optical (NLO) crystals like Rb<sub>2</sub>ScB<sub>3</sub>O<sub>6</sub>F<sub>2</sub> have opened new arenas for next-generation DUV photonic devices. These advancements promise potential applications, from water purification to high-resolution, maskless photolithography, etc. Recent studies have shown the development of several NLO based materials<sup>72-76</sup> for application in DUV devices. Additionally, there are few more prominent review papers<sup>77-81</sup> published in the recent years, that discuss the development and evolution of DUV C LEDs.

#### 4.5 AI-based approaches for design of novel DUV emitters

In the past decade, researchers have stated and proved that computational and AI-based methods are gaining pivotal role in designing novel DUV emitters due to their ability in handling complex datasets of various materials, used in applications related to optimize the device architectures. Several notable Machine learning (ML) frameworks such as stacking ensemble models and Light GBM regression models have been found to rapidly screen ultra-wide bandgap (UWBG) semiconductors, thus enabling identification of promising DUV materials amongst the thousands of similar materials.<sup>82</sup> Integration of ML with first-principles calculations (such as DFT) fine tunes the predictions for ideal (and practical) bandgaps, optical properties and stability.<sup>83</sup> Also, effective AI approaches like SHAP uncover the structure property relationships which reform the material selection.<sup>84</sup> Deep learning models and convolutional neural networks (CNNs) have been often used to extract crucial features that affect the luminous performance of AlGaIn-based DUV LEDs, thus predicting the device efficiencies. Additionally, numerous data-driven optimization methods, including genetic algorithms or reinforcement learning, fine-tune layer structures and compositions, significantly accelerate the discovery and advancing of high-performance DUV emitters.<sup>85</sup>

## 5. Conclusion

DUV LEDs have emerged as sustainable light sources, offering significant advantages over the conventional mercury lamps, in terms of ecofriendly nature and high efficiency. The present review focusses on advancements in AlGaIn-based quantum structures which emerged as promising approaches to develop novel LEDs for notable applications in various fields, such as sterilization, biomedical imaging, and environmental monitoring, as reported in the past decade. The article also discusses the synthesis of novel inorganic phosphor materials which have expanded the application scope of DUV LEDs. Future progress centres on optimizing quantum well designs, enhancing the crystal quality, and improving light extraction methodologies. Additionally, the incorporation of innovative phosphors and nanostructures also revealed new performance metrics, mainly for emission tunability and efficiency. The discussion in this article centres and concludes with innovation of DUV LEDs for application in next-generation devices for global health, safety and sustainability.

## 6. Future Directions

Research on DUV LEDs must focus on overcoming the efficiency barrier through several factors like optimization of quantum well structures, improving high Al content in the AlGaIn crystal quality and enhancing the light extraction techniques. The integration of novel inorganic phosphors and nanostructures offer promising approaches for enhancing the emission efficiency as well as tunability of the spectra towards DUV region. Development of robust, compact, and low-cost packaging materials is essential for real world applications. With an increased demand for applications related to sterilization, biosensing, and environmental monitoring, notable interdisciplinary strategies involving cross cultural disciplines such as materials science, photonics, and device engineering will be essential. The stated advancements will aim for developing next-generation DUV LEDs with enhanced performance, safety, and global applicability.

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Manuscript

## Emotional Freedom Techniques (EFT) and Dopamine Detox: A Neurobehavioral Tool for Stress Management

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**Abstract:** Dopamine dysregulation has become a major driver of behavioral addiction, emotional volatility, and cognitive dysfunction in the age of digital hyperstimulation. From social media and entertainment to processed foods and multitasking, the reward system of the brain is under constant supernormal stimulation and it progressively loses its sensitivity to natural reinforcers. Integrating cognitive restructuring with acupressure-based tapping, Emotional Freedom Techniques (EFT) is an integrative neurobehavioral intervention used to control both emotional and physiological reactions to stress. The effectiveness of this strategy mostly depends on one's capacity to control the emotional withdrawal symptoms and psychological distress following the detox procedure. Although well-known for its ability to treat anxiety, trauma, and cravings, the ability of EFT to modify dopaminergic reward pathways also makes it a hopeful addition to dopamine detoxification plans. Often concomitant with reward-seeking behaviors, chronic stress disrupts the hypothalamic-pituitary-adrenal (HPA) axis, raises cortisol, causes inflammation, and worsens dopamine balance. While EFT has been shown to lower cortisol, proinflammatory cytokines, and subjective stress markers, it also boosts parasympathetic and antioxidant activities. EFT offers people a practical way to negotiate the neuropsychological difficulties of dopamine detox by breaking compulsive behavioral loops and fostering emotional resilience. The biopsychosocial processes of EFT, its effect on neurochemical control, and its bigger therapeutic potential for handling stress-related disorders, behavioral addictions, and emotional dysregulation in a digitally overstimulated world are discussed in this article. This review further explores the neurobiological mechanisms of EFT, its impact on dopaminergic dysregulation, and its therapeutic role in stress-related and behavioral health challenges.

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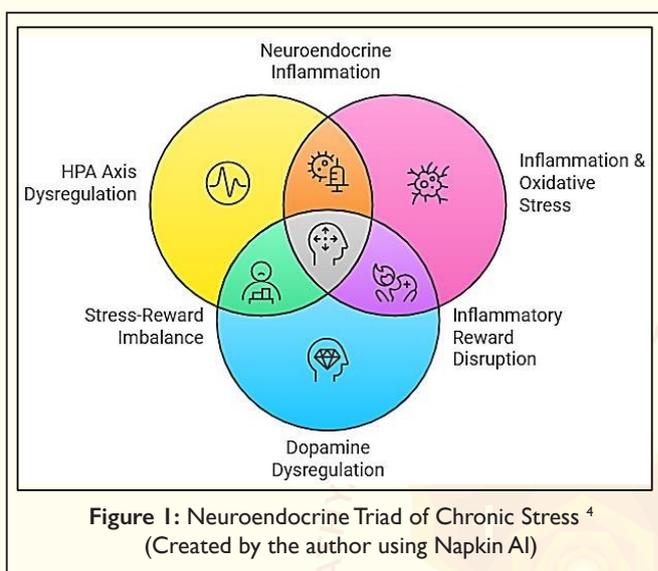
**Keywords:** Emotional Freedom Techniques, dopamine detox, neurobehavioral regulation, stress reduction, neuroplasticity, behavior modification, cortisol.

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## I. Introduction

Emotional Freedom Techniques (EFT) have become well-known as a scientifically based, somatic approach for stress alleviation, emotional control, and trauma healing. EFT combines cognitive therapy with acupressure tapping on particular meridian points to target psychological suffering.<sup>1</sup> People are now more often exposed to hyper-stimulating surroundings through fast-paced living, processed meals, or digital media. Particularly the mesolimbic route, these stimuli constantly activate the dopaminergic reward system, which causes increased impulsivity, reduced motivation, and emotional dysregulation (Figure 1).<sup>2,3</sup>



Emergent as a behavioral treatment meant to restore equilibrium by lowering overexposure to strong reward stimuli, the dopamine detox concept has emerged. This study explores the interaction among stress, dopamine dysregulation, and behavioral addiction and emphasizes how EFT enables a successful dopamine detox. Emerging public health issues in today's hyperconnected digital world are chronic

psychological stress and dopaminergic overstimulation. Prolonged exposure to stress, social media, digital entertainment, and multitask settings can hyperactivate the brain's reward circuitry, particularly the mesolimbic dopamine pathway, contributing to dysregulated mood, addictive behaviors, attention deficits, emotional burnout, and reduced executive functioning.<sup>5,6</sup> Popularly known as "dopamine detox," this phenomenon reveals a growing need for behavioral resets that cut overstimulation and help to restore neurochemical equilibrium. Simultaneously, chronic psychological stress, usually brought on by unaddressed trauma, work load, or emotional suppression, keeps upregulating the hypothalamic pituitary adrenal (HPA) axis and increasing overall cortisol levels. This causes immune dysregulation, chronic inflammation, oxidative stress, and poor hepatic detoxification.<sup>7,8</sup>

These neuroendocrine problems support one another, resulting in a circular cycle of emotional reactivity, dopamine dysregulation, and physical imbalance. Against this background, there is an increasing demand for integrative mind-body therapies that solve the underlying causes of both psychological stress and neurobehavioral imbalance. Developed in the 1990s by Gary Craig, Emotional Freedom Techniques offers a strong intervention that synergistically combines elements of cognitive-behavioral therapy (CBT), exposure therapy, and acupressure-based tapping on meridian points. EFT seeks to neutralize emotional triggers by reprocessing negative emotions while concurrently stimulating peripheral acupoints, which send calming impulses to the limbic system and downregulate sympathetic nervous activity [1]. EFT has been demonstrated to significantly lower cortisol levels, change amygdala activity, boost parasympathetic tone, and improve psychophysiological resilience.<sup>4,9</sup> By lowering psychological pain, improving emotional regulation, and encouraging parasympathetic dominance, EFT may indirectly help to achieve dopamine homeostasis and help break patterns of overstimulation or addictive engagement with foods, chemicals, or technology.<sup>10,11</sup> Thus, EFT not only relieves emotional suffering but may also support "dopamine detox" by settling reward circuits and conditioning patterns of behavior driven by quick gratification. Recent research has

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also investigated EFT's possible effects on dopaminergic signaling and behavioral regulation. Often, common neurobiological pathways, including dopamine and cortisol, define stress and compulsive behaviors.<sup>11</sup>

In this review, we explore EFT's role as a neurobehavioral strategy for stress regulation and dopamine detoxification. We examine the psychophysiological mechanisms of EFT, including its effects on the HPA axis, cortisol modulation, autonomic balance, immune response, and oxidative stress markers. Furthermore, we discuss how this integrative technique can be a cost-effective, non-pharmacological intervention to support emotional regulation, neurochemical balance, and detoxification processes, with implications for mental clarity, behavioral reset, and long-term well-being.

## 2. Methodology:

A detailed literature search was done to find relevant papers published between January 2000 and August 2025. The search was performed using major electronic databases - PubMed, Scopus, Web of Science, and Google Scholar. The search approach was developed using a mix of keywords "Emotional Freedom Techniques" (EFT), "dopamine detox," "stress reduction," and "behavioral addictions". operators to catch a wide but concentrated spectrum of publications. Database-specific filters, including publication type, language, and research design, helped to further focus the search. Studies were considered appropriate for inclusion if they were experimental studies, systematic reviews, or peer-reviewed clinical trials looking at the physiological or behavioral consequences of EFT especially in connection to stress reduction, dopamine control, or the attenuation of behavioral addictions. Case reports, conference abstracts, non-peer-reviewed papers, opinion pieces, and studies written in languages other than English all underwent exclusion criteria, as these sources often lack methodological discipline or standardized reporting of results. This strict and clear methodical strategy improves the dependability and credibility of the review in addition to lowering selection bias, hence providing a dependable base for combining present data on EFT's behavioral and physiological effects.

## 3. Stress, Inflammation, and Detoxification:

Research on neurobehavioral and integrative health has increasingly focused on the connection between chronic stress, systemic inflammation, compromised detoxification, and dopamine dysregulation. Marked by high cognitive load, emotional suppression, and continual digital interaction, the contemporary lifestyle results in sustained activation of the hypothalamic-pituitary-adrenal (HPA) axis and overstimulation of the mesolimbic dopamine pathway.<sup>6</sup> Ultimately, these parallel yet interconnected neuroendocrine systems affect physical resilience or dysfunction, regulating how the body perceives threats, rewards, and stress.

**3.1 Stress and Dysregulation of the HPA Axis:** Psychological stress sets the HPA axis off, therefore triggering a cascade in which the hypothalamus releases corticotropin-releasing hormone (CRH), which activates the anterior pituitary to secrete adrenocorticotropic hormone (ACTH), therefore causing the adrenal cortex to secrete cortisol, the body's main stress hormone. Although cortisol helps short-term stress by raising glucose availability and inhibiting non-essential bodily activities, chronic hypercortisolemia turns pathological. Prolonged cortisol exposure results in a pro-inflammatory state characterized by elevated cytokines such as tumor necrosis factor-alpha (TNF- $\alpha$ ) and interleukin-6 (IL-6) as well as immune suppression and compromised neuroplasticity.<sup>7,8</sup> Overactivation of the HPA axis also upsets neurotransmitter equilibrium, including dopamine signaling,

which is essential to motivation, learning, and behavioral reward. Compulsive behaviors, burnout, anxiety, and substance use disorders<sup>5</sup> are increasingly linked with this neurochemical imbalance. Under this heading, the notion of dopamine detox that is, a behavioral and neurochemical reset from chronic overstimulation has found support. Downregulation of stress channels that support reward-seeking and impulsivity under pressure is a vital part of this reset.

**3.2 Inflammation, Oxidative Stress, and Impaired Detox:** Sustained pro-inflammatory conditions result from cortisol increases brought on by chronic stress. High cytokine levels aggravate oxidative stress even further characterized by an overproduction of reactive oxygen species (ROS) and a depletion of antioxidant defenses such as glutathione (GSH), superoxide dismutase (SOD), and catalase. Contributing to early cellular aging and vulnerability to chronic diseases, this redox imbalance causes lipid peroxidation, mitochondrial dysfunction, and DNA damage.<sup>12,10</sup> Additionally, oxidative stress and inflammation impede the body's detoxification ability, especially the liver's Phase I and Phase II elimination systems. Enzymatic oxidation (e.g., cytochrome P450 system) in Phase I detoxification transforms lipophilic poisons into intermediate substances, sometimes more reactive and damaging if not rapidly processed. Phase II involves conjugation reactions (e.g., methylation, sulfation, glucuronidation) that make these compounds water-soluble for excretion. Both phases need a strong antioxidant system, especially glutathione, to run. Detoxification becomes inadequate when antioxidant reserves are depleted under chronic stress, which permits the accumulation of toxic metabolites and exacerbates systemic inflammation and neurotoxicity.<sup>1,9</sup>

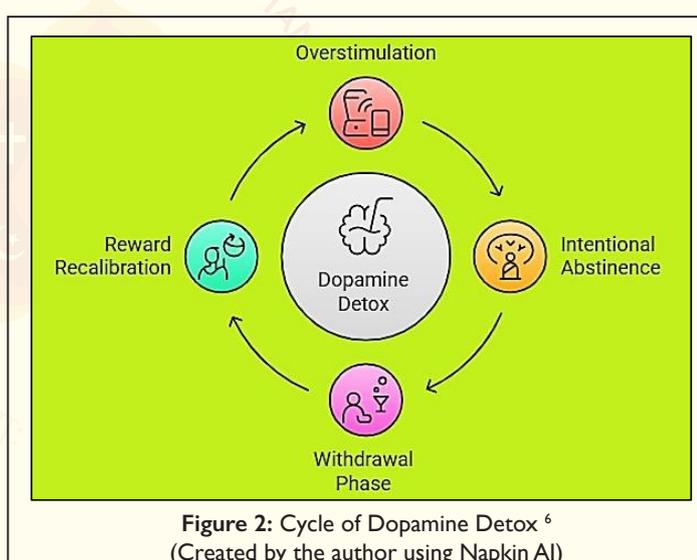
**3.3 Dopamine dysregulation and behavioral exhaustion:** Parallel to the physiological effects of chronic stress is dopamine dysregulation, especially in the mesolimbic reward pathway, involving the ventral tegmental area (VTA) and the nucleus accumbens. Dopamine plays a central role in reinforcing behaviors, attention, pleasure, and motivation. In the context of overstimulation, via excessive digital content, stimulants, or emotional distress, dopamine receptors may become desensitized, leading to a blunted reward response, decreased motivation, and increased compulsive behaviors.<sup>6,11</sup> While necessary for survival-driven behaviors, modern activities like social media use, instant messaging, and video streaming hijack this pathway by offering artificial surges of dopamine.<sup>13</sup> This neurochemical exhaustion promotes psychological symptoms, including anxiety, impulsivity, emotional numbing, and attention dysregulation. Additionally, stress-driven elevations in cortisol and inflammatory cytokines can negatively impact dopaminergic transmission in key brain regions like the prefrontal cortex, undermining emotional regulation and executive function.<sup>8</sup> Consequently, individuals often develop addictive behaviors accompanied by stress, fatigue, and reduced self-efficacy.<sup>14</sup>

Chronic exposure to highly stimulating environments, such as digital overload, addictive substances, or constant stress, can significantly disrupt the brain's reward system. Over time, this leads to reduced sensitivity of dopamine receptors, making it harder to experience pleasure from everyday activities. As a result, individuals often develop hedonic adaptation, requiring increasingly intense stimuli to achieve the same level of satisfaction. This imbalance not only weakens impulse control but also contributes to emotional exhaustion and burnout, impairing overall well-being and mental resilience. Together, this triad of stress-induced HPA dysregulation, inflammatory-oxidative imbalance, and dopamine exhaustion creates a self-perpetuating cycle underlying several chronic conditions, ranging from metabolic syndromes and mood disorders to addictive behaviors. Interventions that can regulate both neurocognitive processes and biochemical pathways will help to address these imbalances. Emotional Freedom Techniques (EFT) here provide a hopeful neurobehavioral therapy that can break this cycle by lowering stress reactions, regulating dopamine-driven behaviors, and restoring detoxification ability. The following chapters discuss how EFT targets these systems to achieve emotional, physical, and biochemical balance.

This review uses the term “dopamine detox” in an intellectual and behavioral context rather than a strict neurochemical one. It is a process of behavioral recalibration marked by the intentional decrease or momentary abstinence from high-frequency external stimuli like social media, gaming, or other instant-reward actions that are known to engage and perhaps dysregulate the reward system of the brain. Restricting such stimuli helps people to promote an indirect neurochemical recalibration that lets the dopaminergic signaling pathways of the brain regain a more balanced baseline throughout time. Notably, the word emphasizes a behavioral strategy meant to restore dopamine rather than suggesting the physical depletion, removal, or direct detoxification of it. Dopaminergic system’s inherent sensitivity and activity.

#### 4. The Concept of Dopamine Detox

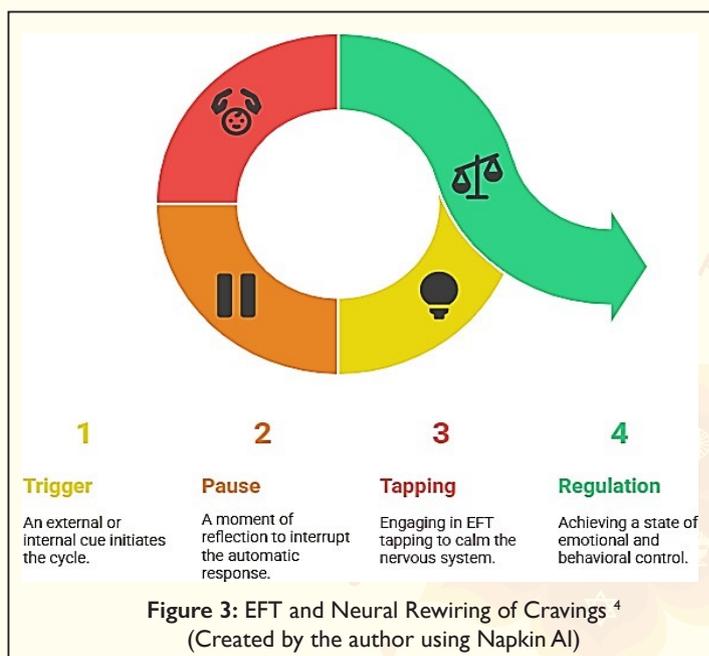
As a means to fight overstimulation and reward system exhaustion, the idea of dopamine detox has become increasingly accepted in behavioral neuroscience and popular psychology. Though the name might suggest otherwise, dopamine detox aims to momentarily lower dopamine-triggering stimuli so that the brain’s reward system can reset and calibrate (Figure 2),<sup>15,6</sup> not to eradicate dopamine, a crucial neurotransmitter involved in motivation, reward anticipation, attention, and motor control. People are bombarded with high-frequency, low-effort sources of dopamine spikes in modern situations by regular interaction with digital devices, social media alerts, ultra-processed foods, caffeine, and on-demand entertainment. This constant exposure to gratifying stimuli causes dopaminergic desensitization, whereby more frequent and more intense stimulation is needed to get the same level of pleasure, a phenomenon akin to tolerance seen in substance use disorders.<sup>5,11</sup>



Dopamine detoxification entails a time of voluntary abstinence from these obsessive sources of pleasure, therefore producing a low-stimulation environment that advances neuroplastic repair, self-reflection, and the development of more balanced behavioral patterns.<sup>16</sup> Usually, people abstain from activities like scrolling through social media, binge-watching content, multitasking with electronic gadgets, taking stimulants like caffeine, or indulging in fast food during a detox phase since each of these stimulates the mesolimbic reward pathway and floods the brain with dopamine. The aim is to restore sensitivity to natural, effort-based rewards such as interpersonal connection, physical activity, focused work, or mindfulness practices.<sup>17</sup> By allowing the brain’s baseline dopamine signaling to normalize, this reset process is thought to boost motivation, impulse control, and general mental clarity. The initial phase of dopamine detox also presents difficulties, though. Many people have withdrawal-like symptoms, including boredom, restlessness, irritability, anxiety, mental fatigue, and strong hunger for immediate gratification.<sup>18</sup> These reactions are linked to both psychological dependence and neurochemical adaptation as the brain briefly fights to adjust to reduced levels of stimulation. Many people revert to obsessive behaviors without sufficient coping mechanisms,

therefore negating the advantages of the detoxification procedure. Emotional Freedom Techniques (EFT) could be of great help at this phase by combining focused cognitive processing with somatic tapping to control emotional suffering and autonomic excitement. By interacting the amygdala–hippocampus–prefrontal cortex network, EFT has been proven to lower cortisol levels, reduce anxiety, and moderate craving responses, all of which are engaged in both stress regulation and addictive behaviors.<sup>1,4</sup>

Moreover, by helping to promote emotional acceptance and diminish the inclination to escape pain, EFT can alleviate the psychological withdrawal symptoms linked with dopamine detox, therefore



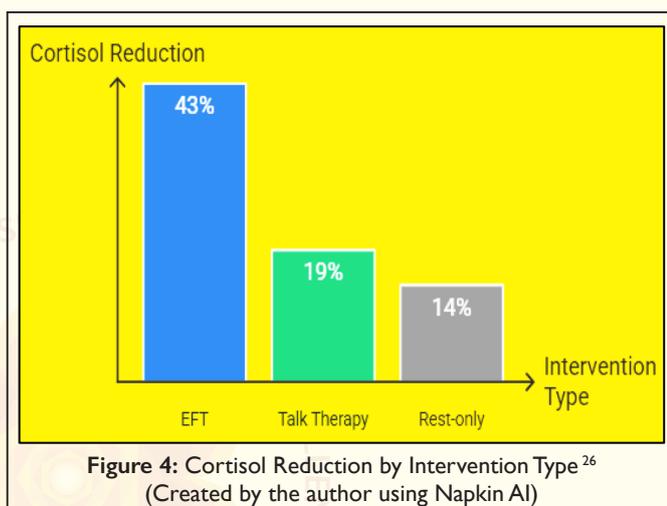
enabling people to stay committed to better behavioral change and long-term neurochemical stability.<sup>11,9</sup> Hence, dopamine detox is less about suppressing behaviors and more about strategic self-regulation. By means of planned behavioral abstinence and careful reintegration of natural rewards, the dopaminergic pathways in the brain can recover their sensitivity and effectiveness. Integrating evidence-based therapies like EFT during this period may also encourage permanent rewiring of bad reward-seeking channels, therefore sustaining a more balanced and emotionally healthy lifestyle.

## 5. Emotional Freedom Techniques (EFT): Overview

Combining concepts from cognitive behavioral therapy (CBT) and somatic acupressure stimulation, emotional freedom techniques (EFT) provide a dual-modality approach aimed at both the psychological and physical components of emotional dysregulation. Starting with the individual recognizing a painful emotion, craving, or traumatic memory and measuring its subjective intensity on a numeric scale (usually 0 to 10). Following this is the crafting of a “setup statement,” which acknowledges the problem yet affirms self-acceptance, frequently phrased as, “Even if I feel anxious, I thoroughly accept myself.” While the person concentrates on the painful emotion, they concurrently tap on nine acupressure points reflecting major meridians employed in traditional Chinese medicine, points on the face, hands, and upper torso.<sup>1,4</sup> Often, within a few rounds, this tapping sequence is repeated until the reported distress level drops dramatically. Neurophysiological studies imply that this structured engagement with both emotional cognition and tactile input helps the amygdala, hippocampus, and medial prefrontal cortex, brain regions central to threat detection, emotional memory, and executive control, regulate. Hyperactivation of the amygdala is often noted in anxiety, PTSD, and addiction-related disorders; it is mostly involved in triggering the fight-or-flight response.<sup>19</sup> Through EFT, reactivation of the emotional memory trace in a secure environment, combined with calming tactile stimuli, seems to promote emotional reconsolidation and desensitization, therefore allowing for the formation of fresh neuronal connections. Functional MRI and EEG investigations have validated this mechanism by demonstrating discernible changes in brain wave activity and lower limbic activation following EFT sessions (Figure 3).<sup>4,20</sup> Targeting both cognitive reappraisal and autonomic modulation, EFT positions itself as a potential instrument for fast emotional relief, particularly helpful during times of stress, withdrawal, or dopamine detox, when emotional response and appetites are increased.<sup>20</sup>

## 6. EFT in Stress Reduction and Cortisol Modulation

Among the most thoroughly confirmed physiological effects of Emotional Freedom Techniques is their ability to greatly lower cortisol, the body's main glucocorticoid hormone engaged in the stress response. Central in mobilizing energy, controlling inflammation, and modulating focus and arousal, cortisol, released by the adrenal cortex in response to hypothalamic-pituitary-adrenal (HPA) axis activation, helps to accomplish this. But when cortisol is chronically raised, especially by weakening the regulating activities of the prefrontal cortex and enhancing limbic system reactivity,<sup>7,8</sup> it causes immune suppression, cognitive impairment, and neurochemical imbalance. These effects are strongly related to dysregulation in dopaminergic pathways, where high cortisol lowers dopamine receptor sensitivity and executive control, hence increasing reward-seeking behavior and emotional impulsivity.<sup>5,6</sup> In a single session, EFT may reduce salivary cortisol levels by up to 43%, surpassing both talk therapy and rest-only control groups, which displayed a maximum reduction of 14%, according to a landmark randomized controlled study by Church *et al.*<sup>21</sup> (Figure 4). Along with this quick drop in cortisol came notable improvements in subjective ratings of anxiety, mood, and emotional control. With a shift from sympathetic dominance (fight-or-flight) to parasympathetic recovery (rest-and-digest), such cortisol reductions reflect a rebalancing of the autonomic nervous system, a critical change for reversing the biochemical damage caused by chronic stress. These findings have since been duplicated in several clinical groups, including patients with post-traumatic stress disorder (PTSD), fibromyalgia, and work-related stress.<sup>9,22</sup>



Crucially, by calming the physiological stress reaction of the body, EFT helps more adaptive reward processing, boosts impulse control, and raises the capacity to interact with natural, effort-based rewards, which are crucial for restoring dopaminergic sensitivity. EFT also supports more adaptive reward processing, enhances impulse control, and helps to reduce amygdala hyperactivation, which are necessary for normalizing cortisol levels, and so directly matches the aims of dopamine detoxification. Hence, EFT helps to control both stress physiology and reward circuitry, making it an especially appropriate instrument for people going through dopamine detox, therefore acting not just as a psychological treatment but also as a biochemical modulator.

## 7. EFT for Cravings, Emotional Triggers, and Habits

Research shows that Emotional Freedom Techniques can effectively reduce food cravings, cigarette addiction, and compulsive behaviors. EFT helps address cravings, emotional reactions, and obsessive actions linked to poor reward processing and emotional self-control. Growing clinical studies show that EFT can greatly lower the intensity and frequency of food cravings, nicotine dependence, and emotion-driven behavioral patterns.<sup>29,23</sup> In the early phases of dopamine detoxification, a time defined by increased vulnerability to withdrawal symptoms like restlessness, irritability, impulsivity, and emotional suffering, these advantages are especially pertinent. Cravings are sometimes learned responses to emotional or environmental cues, not only chemical impulses. Boredom, stress, or fatigue, for instance, can activate limbic system structures such as the amygdala and insula, which link negative affect with regular behaviors aimed at quick reward.<sup>6</sup> By simultaneously stimulating acupressure points and engaging the prefrontal cortex via conscious cognitive processing, EFT breaks

this neurobehavioral cycle. This mix helps people become more conscious of the hunger cue, lower the emotional intensity connected with it, and decouple the automatic cue-response connection that normally motivates obsessive behavior.<sup>1</sup>

Clinical studies have shown that even short EFT treatments can lead to notable decreases in emotional eating, craving strength, and substance use impulses. For example, Stapleton et al.<sup>24</sup> found that patients who received EFT for food cravings showed major decreases in both the strength and frequency of cravings as well as improved dietary restraint and lowered emotional eating, effects that were sustained at six-month follow-up. Effective reductions in cigarette use and desire intensity using EFT-based interventions were observed, underlining its potential as a non-pharmacological support tool in habit cessation and addiction recovery. Significantly, EFT also improves emotional tolerance, the capacity to stay present with unpleasant internal states like boredom, worry, or resentment without turning to regular escape actions. EFT calms the autonomic nervous system and supports emotional control, therefore forming a buffer between impulse and action and allowing the person room and time to select more helpful responses. This is especially critical during the early stages of dopamine detoxification when the brain's reward pathways are resetting and people are most vulnerable to falling back into quick pleasure activities. Especially when incorporated into more general wellness regimens or behavioral therapies, repeated EFT use over time can promote habit change, increased behavioral flexibility, and long-term dopaminergic equilibrium.<sup>23</sup>

### 8. Reconditioning the Brain's Reward System with EFT

Every time EFT is practiced during a craving or stress response, it introduces a new sensory-cognitive feedback loop over time, which can change neurobehavioral patterns. Instead of automatically responding to the craving or emotional urge, whether it's reaching for a phone, a snack, or a cigarette, the person is urged to stop, recognize the emotional state, and engage in the tapping series while keeping conscious awareness of the inside experience. This purposeful disturbance of the conditioned response lets the amygdala-centered stress circuits be bypassed, hence giving the prefrontal cortex time to engage and exert regulatory control.<sup>1,4</sup> Through repeatedly substituting deliberate self-regulation for impulsive actions, EFT breaks automatic cue-response loops usually strengthened in dopamine-driven addictions. This repetition produces a fresh associative connection in the brain between emotional triggers and self-soothing rather than instant pleasure over time. Based on the idea of neuroplasticity, where repeated emotional events and behavioral choices may change synaptic connections and rewire established responses,<sup>25,26</sup> this mechanism is grounded. Even when confronted with previously dysregulating stimuli, tapping's calming somatosensory input strengthens a parasympathetic condition and improves feelings of agency, serenity, and emotional clarity. As this new neural route becomes more established, people start to link emotional activation with safety and self-regulation rather than with impulsivity or escape. This change is very important for maintaining the benefits of dopamine detox,

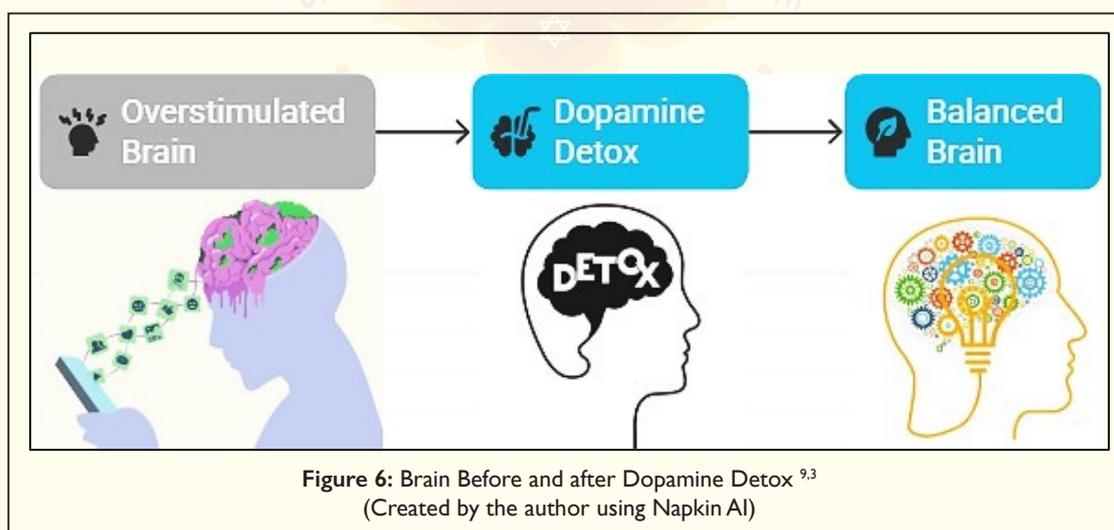
Characteristic	EFT Tapping
 <b>Brain Target</b>	Amygdala (↓)
 <b>Emotional Effect</b>	Hippocampus (↔)
 <b>Cognitive Effect</b>	Prefrontal Cortex (↑)
 <b>Overall Effect</b>	Calms fight/flight
 <b>Outcome</b>	Emotional regulation
 <b>Benefit</b>	Reduced stress

Figure 5: Neurophysiological Effects of EFT on Stress Regulation<sup>25</sup>  
(Created by the author using Napkin AI)

whereby sustained success depends not only on temporary abstinence from strong dopamine stimuli but also on developing continuous emotional resilience and behavioral flexibility. EFT helps this internal transformation, therefore becoming more than just a tool for stress reduction; it becomes a neurobehavioral training tool matching the mind and body towards deliberate, health-promoting responses. Thus, EFT supports **long-term neuroplastic changes** needed for sustained dopamine detox success (Figure 5).<sup>25</sup>

### 9. Integrative Benefits of EFT in Dopamine Detox

Though theoretically straightforward, dopamine detox offers several physical and mental obstacles that frequently prevent consistent behavioral change. When people refrain from high-dopamine stimuli such as digital gadgets, processed foods, or instant entertainment, they typically experience a range of withdrawal-like symptoms, including anxiety, cravings, restlessness, emotional flatness, and disturbed sleep. By activating both the cognitive-emotional centers and somatosensory regulatory pathways, Emotional Freedom Techniques (EFT) provides multidimensional support throughout the detoxification process. Anxiety and restlessness, which result from limbic hyperactivation as well as the abrupt cessation of regular sources of stimulation, are among the most immediate obstacles during dopamine detox. Along with its proven capacity to drastically reduce cortisol levels, EFT's calming impact on the amygdala and autonomic nervous system helps to swiftly lower physiological arousal and emotional turmoil.<sup>21,10</sup> EFT also interferes with the cue-response cycle during episodes of craving or compulsive urges by bringing structured meridian tapping, which gives other sensory information as the brain reprocesses the emotional driver behind the urge. Building tolerance to delayed pleasure, a major objective in dopamine detox,<sup>9,19</sup> and rewiring the dopaminergic reward system are helped by this process.



People in the digital age are more and more likely to have an overstimulated brain as they are constantly exposed to high-reward incentives, including social media, online gaming, and ongoing digital contacts. This overstimulation interferes with the brain's normal reward systems, resulting in emotional dysregulation, impulsivity, attention deficits, and behavioral addictions.<sup>6,27</sup> The practice of dopamine detox has become popular as a behavioral therapy intended to lower overstimulating inputs and let the brain's reward system recalibrate<sup>15</sup> in response to this neurochemical overload.

By brief abstinence from high-dopamine activities, people may reset their neural thresholds and start to enjoy joy from simpler, more natural stimuli. One of the most often seen symptoms of dopamine detoxification, though, is emotional indifference or numbness brought on by decreased sensitivity to natural rewards. Emotional Freedom Techniques (EFT) are especially helpful at this point; they help people to sit with unpleasant inner feelings without using distraction or aversion, therefore building emotional resilience and presence.<sup>1</sup>

Over time, this practice enhances emotional granularity, allowing for a richer, more nuanced emotional experience and encouraging engagement with subtler, more sustainable sources of joy. In the context of digital withdrawal often marked by irritability, anxiety, and reduced concentration, EFT promotes parasympathetic nervous system dominance, which helps shift the brain from hyperarousal towards a calm, regulated state.<sup>20</sup> The disruption of sleep cycles brought on by disparities in cortisol, melatonin, and autonomous regulation is another difficulty during dopamine detox. Through these mechanisms, EFT supports the transition from an overstimulated brain to a balanced brain (Figure 6), not only by addressing psychological symptoms but also by aiding neurobiological homeostasis. Therefore, it offers an integrative, mind-body approach to navigating the complex process of dopamine detox and long-term cognitive-emotional recovery.<sup>9</sup>

While EFT is generally considered safe and non-invasive, certain constraints exist. These include variability in practitioner expertise, inconsistent adherence in self-guided use, and the possibility of transient emotional discomfort during exposure to distressing memories. EFT should be used with caution in individuals with severe psychiatric disorders and ideally under professional supervision. Despite promising evidence, a key limitation is the lack of longitudinal neuroimaging and neurochemical biomarker studies to directly assess dopaminergic and cortisol regulation during and after EFT-assisted dopamine detox. Future research should integrate functional MRI, PET, and biochemical assays to provide objective evidence of these mechanisms. Variability in EFT delivery and heavy reliance on self-reported outcomes also highlight the need for standardized protocols and controlled multi-center trials.

## 10. Limitations and Future Directions

Although the current evidence supporting Emotional Freedom Techniques as a method for stress reduction, desire control, and emotional control is strong, several restrictions and research gaps need further study. Most studies so far have concentrated on short-term results or separate treatments, usually using healthy adult populations with little diversity in age, ethnicity, medical history, or environmental exposure.<sup>4</sup> This limits the overall generalizability of results to actual environments where chronic stress, trauma, and behavioral addiction co-exist among larger demographic groups. Future research should aim to include more varied populations, including teenagers, older adults, people with comorbid psychiatric or neurodevelopmental conditions, and those exposed to high-risk digital surroundings.<sup>22,3</sup>

Few empirical investigations have directly assessed neurochemical or structural brain alterations following constant EFT application, even though narrative and clinical evidence indicate that EFT helps dopamine detoxification. Functional MRI (fMRI) and electroencephalography (EEG) could provide insightful knowledge on how EFT affects reward circuits, emotional regulation networks, and prefrontal-limbic connectivity over time. Furthermore, to determine the most successful and long-lasting behavioral approaches, EFT-supported phasic detoxification treatments

where people progressively decrease dopamine-reinforcing activities should be compared with cold-turkey abstinence models. Finally, the best timing and order of EFT inside dopamine detox regimens is still underappreciated. Researching whether EFT is most effectively used during the anticipatory phase, during peak withdrawal, or as a maintenance tool post-detox could greatly improve implementation fidelity and result reliability. Refining and thoroughly testing EFT as a scalable, evidence-based treatment is a crucial first step toward integrated behavioral health and customized neurotherapeutic care as digital overstimulation and obsessive behavior keep increasing worldwide.<sup>5,11</sup>

## 11. Conclusion

The notion of dopamine detox has become increasingly popular in today's overstimulated and digitally saturated world as a behavioral reset strategy to restore neurochemical equilibrium, increase mental clarity, and regain control over compulsive behaviors. Though the idea of refraining from immediate-reward activities such as scrolling, binge eating, or multitasking seems simple, the detoxification process sometimes involves emotional discomfort, including anxiety, irritability, cravings, weariness, and sleep problems. These reactions go beyond just mental ones; they point to underlying neuroendocrine imbalances, including the HPA axis, limbic system, and dopaminergic signaling pathways. Hence, dopamine detox success relies not only on avoidance but also on the individual's ability to self-regulate, handle emotional strain, and promote constructive coping mechanisms during the reset phase.

Emotional Freedom Techniques offer a strong and easily available response to this issue. EFT is a non-invasive, evidence-based technique combining cognitive reappraisal with acupressure stimulation that has been found to dramatically reduce cortisol, reduce limbic hyperactivation, and rewire bad cue-response links. These consequences are especially pertinent during dopamine detox, when emotional dysregulation and impulsive actions are most visible. EFT helps people to stay present with their pain rather than retreating into temporary enjoyments by activating the parasympathetic nervous system, increasing emotional resilience, and enhancing neuroplasticity. This helps over time to develop new neural paths linking emotional triggers with calm, agency, and deliberate action, instead of compulsivity. Furthermore, EFT's usefulness reaches beyond quick symptom alleviation. With its ability to adjust across several populations and environments and its impact on inflammation and stress markers, it is a useful complement in integrative health programs geared at emotional well-being, detoxifying, and behavioral change. Incorporating EFT can improve both the effectiveness and sustainability of such treatments as dopamine detox grows more pertinent in clinical, educational, and occupational well-being areas. With little obstacles to adoption and expanding empirical evidence, EFT has the potential to bridge the gap between emotional control and neurobehavioral recovery, therefore providing a whole approach to thrive in a high-stimulus setting.

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Article

## Confidence in Connectivity: Tracing Government Commitment through India's UDAN Scheme

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**Abstract:** Since its launch in 2017, India's Ude Desh ka Aam Naagrik (UDAN) scheme has attempted to enhance regional air connectivity by incentivizing airlines to fly to unserved and underserved airports. Current literature has focused mainly on the operational difficulties and infrastructure deficiencies of the scheme; however, comparatively less attention has been directed towards the evolution of government confidence in UDAN's original mission over subsequent rounds of implementation. This study examines that growth through a study of the ratio of awarded routes to achieve UDAN's mission of linking less inhabited smaller cities with more inhabited urban areas. Using city population to create a classification system as a tool to determine mission-aligned routes, this study employs linear regression analysis across all five UDAN rounds. The results demonstrate a statistically significant enhancement in mission-compatible trajectories, reflecting governmental self-assurance and strategic intent in augmentation over time. The outcomes add to end-to-end understandings of policy learning and adjustment in the public sector for large-scale regional development initiatives.

**Keywords:** UDAN Scheme, Regional Air Connectivity, Public Policy Evaluation, Government Scheme Confidence, Urban-Rural Linkages

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### Introduction

Since the liberalization of India's economy in the 1990s, air travel has increasingly become a core tenet of national development alongside regional balance and economic integration. Although the nation's airline sector has consistently grown over the period, air transport has consistently been highly concentrated in only a handful of major metropolitan areas, keeping much of the country geographically and economically isolated in return. In response to the growing issue, the government launched the "Ude Desh ka Aam Naagrik" which translates as "Let the common citizens of the country fly," and is commonly

referred to as the UDAN scheme in 2017 under the National Civil Aviation Policy, specifically aiming to make air transport more affordable to the everyday citizen through the enhancement of regional air connectivity. Through the development of government subsidies, route monopolies, and price caps, UDAN aimed to create an incentive for airlines to fly routes that aim to connect unserved and underserved airports in India.

While the objectives of UDAN have been widely acknowledged, much of the current literature surrounding the scheme has been focused on its operational challenges and if it is possible to connect and reconnect regional airports. However, there has been comparatively less attention to how government confidence in the program has changed over iterative rounds of implementation, as the scheme has awarded route subsidies in groups (e.g., “UDAN 1.0,” “UDAN 2.0,” and “UDAN 3.0” reflect three different instances where routes were awarded). This evaluation is fascinating to analyze, as it offers insights into how large-scale public schemes adapt and mature over time in terms of strategic commitment to the government’s underlying goals.

This paper presents a method of quantifying the Government of India’s belief in UDAN by tracking the proportion of routes that fulfil the scheme’s intent of connecting underserved, low-density regions to larger hubs. Instead of measuring operational success or profitability of routes, this approach looks at intention embedded into the route subsidy itself. Using a classification system based on population density, this study analyzes the development of route patterns from UDAN 1.0 through UDAN 5.3.

This study hypothesizes that the faith the Government of India holds in the UDAN scheme will increase over time, reflected in the form of a higher percentage of mission-aligned routes. By employing official Ministry of Civil Aviation route data and performing a linear regression analysis, this study tests this hypothesis.

## Materials and Methods

This study draws on publicly available reports published by the Ministry of Civil Aviation (MoCA) that list routes awarded under the UDAN scheme. Data was compiled for each round of route awards, starting with UDAN 1.0 in 2017 through to UDAN 5.3 in 2024. For the sake of consistency and comparison between rounds, sub-rounds (i.e., UDAN 4.2 and UDAN 5.3) were recategorized under their parent round categories (UDAN 4.0 and UDAN 5.0, respectively); this is due to the notion that UDAN rounds 1.0 through 3.0 did not have any sub-rounds. This provides a more accurate longitudinal comparison, minimizing distortions caused by small or specialty sub-rounds.

Each awarded route included both the departure and arrival cities, the airline operating said route, and the date of commencement. To assess each connection, data from the most recent 2011 census was mapped onto each endpoint for all awarded routes rather than aggregating by state or union territory. By focusing on the population of the departure and arrival cities, the analysis captured whether connectivity improvements were directed toward smaller, less populous, communities aligning with the scheme’s regional equity objectives.

In order to determine if the awarded UDAN routes aligned with the regional connectivity objectives of the scheme, all departure cities and all destination cities were ranked by their total population. The cities were categorized into five groups according to the size of their population: cities that had fewer than 100,000 inhabitants were categorized as Sparse; cities that had 100,000 to 500,000 inhabitants were categorized as Moderately Sparse; cities that had 500,001 to 1,000,000 inhabitants were categorized as Moderate; cities that had between 1,000,001 to 3,000,000 inhabitants were

categorized as Moderately Dense; and cities with a population of more than 3,000,000 inhabitants were categorized as Dense. This setup allowed for implicit differentiation between severely underserved areas and larger, more urbanized cities.

Following the categorization of each city, awarded routes were evaluated by the population categories of their origin and destination cities. A route was categorized as Mission-Aligned if it connected a Sparse or Moderately Sparse city to a Moderate, Moderately Dense, or Dense city. Connections between two low-population cities, i.e., Sparse–Sparse or Moderately Sparse–Moderately Sparse pairs, were not included as Mission-Aligned, as these routes were not aligned with the program's strategic objective of linking remote areas to more densely populated urban hubs. This classification approach operationalizes UDAN's original mission by giving precedence to routes that increase access between small towns and large population centers, not simply connecting isolated or otherwise small areas to one another.

Although it is true that connections between two smaller or remote cities may contribute to regional development, this study defines "Mission-Alignment" narrowly in accordance with the UDAN scheme's emphasis on linking underserved regions with major urban centers as the the program's intent has been described as an approach to enhance accessibility by connecting unserved and underserved airports to larger markets, where passenger demand, infrastructure capacity, and network spillover effects are greater. Routes connecting two low-population cities, though potentially valuable for localized connectivity, generally do not advance this specific hub-linking objective that underpins the program's initial design. As such, these routes were excluded from the Mission-Aligned category to maintain fidelity to UDAN's stated goal of integrating smaller towns into the broader national air network rather than developing isolated regional pairs. Nevertheless, the potential developmental importance of remote-to-remote connections is acknowledged, and future research should expand such framework to evaluate their unique role in fostering intraregional accessibility. Once all routes were classified as Mission-Aligned or Not Mission-Aligned, the proportion of Mission-Aligned routes to each primary UDAN round was calculated. For an apples-to-apples comparison across rounds, all sub-rounds such as UDAN 4.2 and UDAN 5.3 were consolidated under their parent phases (UDAN 4.0 and UDAN 5.0, respectively). For each round, Mission-Aligned routes were enumerated and divided by the total number of routes allocated, producing a percentage that served as the key indicator of conformity with UDAN's regional equity goals.

To assess whether government confidence in the UDAN scheme increased over time, linear regression was conducted using the UDAN round number (coded as 1 through 5) as a continuous independent variable and the percentage of Mission-Aligned routes in each round as the dependent variable. This modeling strategy treats each round as a point on a temporal scale, enabling the analysis to test for a directional trend across iterations of the program rather than estimate round-specific differences. This decision reflects the research objective, which is not to compare each round individually, but to determine whether there is a systematic increase in alignment with UDAN's mission over time. The statistical significance of this trend was evaluated by analyzing the slope coefficient and its p-value. A positive and statistically significant slope would indicate that the share of routes adhering to the scheme's regional connectivity goals increased over successive rounds, which serves as a proxy for growing strategic confidence in the program by policymakers.

### Considerations and Potential Biases

While the classification framework based on city population provides a consistent and transparent way to interpret UDAN's regional connectivity mission, several potential sources of bias should be recognized. The use of the 2011 Census of India means that recent demographic and urban growth is not reflected in the dataset, which may slightly influence how certain cities are categorized. Population size alone may also not fully capture the complexity of being "underserved," since the UDAN scheme considers additional factors such as geographic isolation, previous levels of air connectivity, and regional economic disparity. Thus, the threshold values used to define population categories, although logically reasoned, introduce some arbitrariness for cities that fall close to category boundaries.

Despite these considerations, population remains the most appropriate and reliable variable for this analysis. Alternative indicators such as GDP per capita or income-based measures, while valuable, are not consistently available at the city level across India and often lack standardization for public use. In contrast, census population data are comprehensive, uniform, and accessible, providing a practical and credible foundation for large-scale comparative assessment of route patterns.

### Literature Review

Since its launch in 2017, the UDAN scheme has created significant academic interest with researchers examining much of its impacts on regional connectivity, its policy structure, and infrastructure concerns. Much of the current literature acknowledges the intention of the scheme to level the playing field in accessing air travel across the subcontinent; however, evaluations vary depending on the study vantage point. Regardless of such vantage points, three prevailing strands of research have emerged.

First, several studies have focused exclusively on the economic and network viability of the scheme itself and analyzing if the structure of awarded routes promotes sustainable regional aviation networks. Second, there has been a critical assessment of the policy framework itself, which debates the effectiveness of the scheme's design and its alignment with greater national aviation goals and challenges that are encountered during implementation. Lastly, there has been a growing body of works that emphasize the barriers, both infrastructure and operational, that regional airports face that warn that connectivity goals may indeed falter without proper investment in physical and environmental sustainability.

This review synthesizes journal articles from all three of these themes in order to situate the current research within the broader academic literature on regional air connectivity in India.

**Viability and Network Design for Regional Connectivity** One of the most important issues in recent UDAN literature is the economic sustainability of regional air connectivity and the structural framework of the new route networks. According to current research by Sindhvani, Jayaram and Ivanov (2024), long-term sustainability of regional connectivity efforts depends on balancing economic profitability with broader social viability goals.<sup>1</sup> Through the examination of the network structure of UDAN, authors argue that even though the scheme efficiently caters to unserved areas, it is jeopardized when routes become disconnected from hubs or have limited feeder traffic. Their findings demonstrate that a stronger hub-and-spoke strategy with well-performing airports as bases would increase resilience in regional connectivity formed under UDAN.

Similarly, another study by Jose and Ram (2019) examines the effect of UDAN on the structure of India's airport network.<sup>2</sup> They construct the Community Index and the Hubbing Potential Index as tools to evaluate how additional new routes enhance airport connectivity. They summarize that UDAN has had a modest positive impact on regional accessibility but note that the network density still remains high around extremely few dominant hubs. The study substantiates the worry that without strategic alignment into existing airport networks, many new UDAN routes are likely to be operationally exposed when subsidies expire.

Together, these pieces point to a general tension at work in UDAN: the program attempts to make access more popular, but its viability depends on its ability to move successfully through India's aerial network along economic and territorial lines. These findings inform the present study's emphasis on patterns of route selection as a proxy for government learning through strategy over the long-term.

### **Policy Design, Implementation, and Challenges**

Apart from network design, a considerable volume of literature has critically examined UDAN's policy framework and its overall alignment with national aviation goals. Research by Iyer and Thomas offers a critical evaluation of the scheme, arguing that while the policy was novel in the way it sought to address market failures, its design introduced a series of operational risks.<sup>3</sup> They highlight that the viability gap funding mechanism, though necessary to stimulate airlines, also created dependency relationships, making the majority of routes non-viable without continued government subsidy. Furthermore, the authors refer to administrative delays, such as slowness in airport readiness and subsidy payment delays, which undermined initial momentum for the scheme.

To this, one study situates UDAN within India's National Civil Aviation Policy (NCAP) and positions its framework in the context of global trends in aviation liberalization.<sup>4</sup> Vivek (2024) argues that UDAN exhibits a hybrid model, blending market incentives with state intervention, but cautions that lopsided implementation and divided regulatory authority have undermined its success. His analysis suggests that while the theoretical foundations of UDAN are aligned with best practices in spurring regional aviation, its success remains ultimately hostage to more consistent intergovernmental coordination and a more effective feedback loop between policy formulation and ground realities.

In conjunction, these writings place UDAN not simply as a technocratic solution to boost connectivity, but as a multi-dimensional policy experiment that embodies the challenges of organizing massive government programs that balance market logic with developmental objectives. Their critiques highlight the importance of examining how state commitment to UDAN's goals has evolved over time, an emphasis at the center of the present research.

### **Airport Infrastructure, Sustainability, and Barriers**

A third important strand of UDAN research addresses the infrastructural and environmental concerns limiting the program's long-term viability. One study draws attention to the persistence of deficits in airport infrastructure, particularly at regional and remote airports.<sup>5</sup> Sarkate (2024) recognizes that various airports included under UDAN lacked major operational preparedness at the time of route awards, resulting in frequent delays or cancellations of subsidized flights. Sarkate contends that absent parallel investment in airport facilities, safety standards, and supporting logistics, even connectivity efforts that are well-intentioned risk unsustainability after government incentives dwindle.

Additionally, while other studies focused mainly on network viability, one has identified infrastructure as an underlying variable in regional aviation success.<sup>1</sup> Their research shows that poorly developed ground facilities at smaller airports not only affect short-term operating efficiency but also discourage passenger take-up, undermining route load factors and commercial viability over the long term. They emphasize that infrastructure deficiencies add to the challenge of balancing commercial viability with social equity objectives in regional air transport.

When viewed together, these writings underscore that achieving UDAN's goals requires more than subsidy-driven route growth. Physical infrastructure, operational consistency, and long-term viability planning are fundamental determinants of whether or not regional connectivity programs can genuinely democratize air travel. Their work supplements the present study's notes on the way government strategy has evolved—not merely in the quantity of routes granted, but in the strategic confidence placed in routes most directly consonant with regional growth aspirations.

## Results

The proportion of Mission-Aligned routes was calculated for each large UDAN round to calculate the path of government confidence over time. Outcomes are displayed to have a rising trend consistent with the stated objectives of the scheme. Volatility across rounds was seen, although the long-term trend shows a rising emphasis on building underserved cities with the key urban centers.

Some 51.8% of routes granted under UDAN 1.0 were Mission-Aligned. This percentage declined to 44.5% under UDAN 2.0 but picked up significantly to 59.4% under UDAN 3.0. The following rounds also saw a similar trend with 57.0% routes being Mission-Aligned under UDAN 4.0 and 60.4% under UDAN 5.0. Although the first round witnessed a decline during the initial phase, the data show that more percent of routes sequentially depicted the regional equity mission of the scheme as the program advanced.

Table I. Classification Metrics per UDAN Round

Departure	Arrival	UDAN-Aligned	UDAN 1.0	UDAN 2.0	UDAN 3.0	UDAN 4.0	UDAN 5.0
Sparse	Sparse	No	0	22	4	18	16
Sparse	Moderately Sparse	No	1	9	5	8	5
Sparse	Moderate	Yes	1	3	5	10	5
Sparse	Moderately Dense	Yes	1	7	7	7	6
Sparse	Dense	Yes	7	7	9	3	4
Moderately Sparse	Sparse	No	1	9	5	8	5
Moderately Sparse	Moderately Sparse	No	2	8	8	6	2

Moderately Sparse	Moderate	Yes	0	6	4	3	3
Moderately Sparse	Moderately Dense	Yes	2	4	13	13	8
Moderately Sparse	Dense	Yes	4	7	11	3	6
Moderate	Sparse	Yes	1	4	5	10	5
Moderate	Moderately Sparse	Yes	0	6	4	3	3
Moderate	Moderate	No	0	0	2	0	2
Moderate	Moderately Dense	No	2	4	6	7	3
Moderate	Dense	No	5	2	6	1	3
Moderately Dense	Sparse	Yes	1	7	7	6	6
Moderately Dense	Moderately Sparse	Yes	2	4	13	13	8
Moderately Dense	Moderate	No	2	4	6	7	3
Moderately Dense	Moderately Dense	No	4	16	15	2	0
Moderately Dense	Dense	No	3	5	2	0	0
Dense	Sparse	Yes	6	7	9	3	4
Dense	Moderately Sparse	Yes	4	7	11	3	6
Dense	Moderate	No	5	2	6	1	3
Dense	Moderately Dense	No	2	5	2	0	0
Dense	Dense	No	0	0	0	0	0

Table 2. Analytic Measures for All Rounds

Metric	Value	Unit of Measurement
Slope	0.029704	Percentage points per UDAN round (Change in % of mission-aligned routes per round)
Intercept	0.457108	Proportion (i.e., 45.7%) (Estimated % mission-aligned routes when round = 0)
Standard Error (Slope)	0.0167	Percentage points per UDAN round (Uncertainty in the slope estimate)
Standard Error (Intercept)	0.055388	Proportion (Uncertainty in the intercept estimate)
R <sup>2</sup> (Coefficient of Determination)	0.513288	Proportion (unitless) (Share of variance explained by the model)
Standard Error of the Y Estimate	0.05281	Proportion (Average error between predicted and actual % mission-aligned routes)
F-statistic	3.163747	Unitless (Compares model fit vs. a null model)
Degrees of Freedom (df)	3	Count (Sample size minus number of estimated parameters)
p-value (Slope)	0.008823	Probability (0–1) (Likelihood the slope is due to chance)
p-value (Intercept)	0.008367	Probability (0–1) (Same as above, for intercept)

A linear regression test confirmed the presence of a statistically significant positive trend. The slope of the regression line was +2.97 percentage points per round of UDAN, with an R<sup>2</sup> of 0.513, indicating a moderate strength of association. The p-value for the slope was 0.0088, verifying that the trend is statistically significant at  $\alpha = 0.01$ . These results support the study hypothesis that the government's confidence in the objectives of UDAN grew over time, as reflected in the trend shift in route awards.

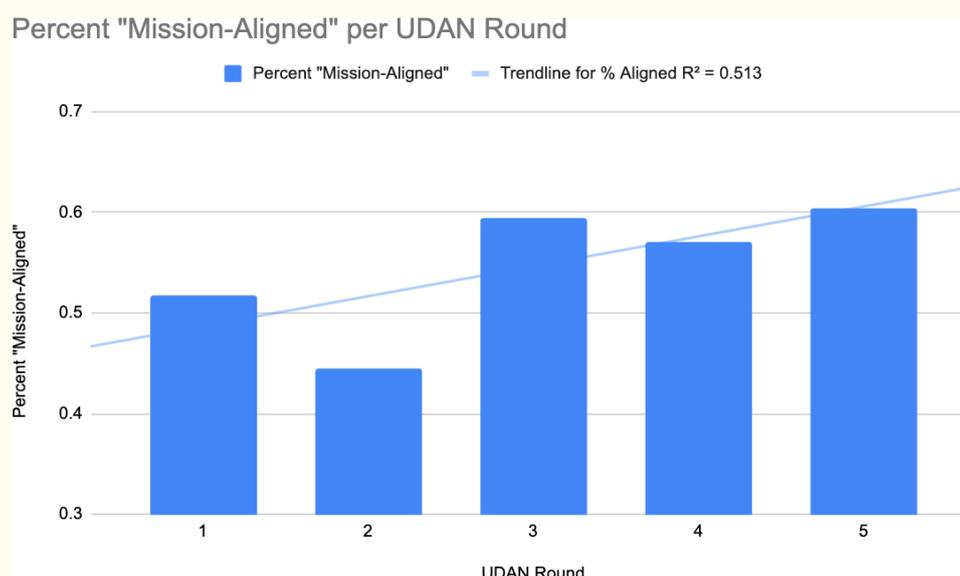


Figure 1: Chart displaying the percentage of Mission-Aligned routes per UDAN Round with trendline.

## Discussion

The results of this study verify a statistically significant rise in the proportion of Mission-Aligned routes under allocation in the UDAN scheme, supporting the hypothesis that government confidence in the initial targets of the program grew over time. Although from the first round to the second and from the third to the fourth, there were minor falls, other rounds showed a transparent trend of rising proportions of routes connecting smaller, unserved towns to larger urban cities. This trend suggests that there was heightened sharpening of strategic priorities as the government progressively preferred routes matching the scheme's regional equity targets as implementation went on. However, it is important to also notice the decline observed in UDAN 2.0, followed by steady rebound in later rounds, which likely reflects early implementation challenges rather than a shift away from the program's regional equity goals. Prior research has shown the effects of administrative delays in airport readiness, limited airline participation, and the need to stabilize the viability gap funding process, of which the analysis performed in this study solidifies such comments. Though as the program matured, these logistical and policy bottlenecks appear to have eased, enabling later rounds, particularly UDAN 3.0 and 5.0, to reflect a more confident and strategically refined approach to mission alignment.

Such findings align with broader theory of policy learning and institutional response that assumes many government programs improve progressively over time cycles of feedback and experience, not by dramatic success. Early scholarly criticisms of UDAN, such as those by Iyer and Thomas (2020) and Vivek (2024), pointed to operational implementation challenges and policy fragmentation that undermined the initial rounds of the scheme. However, the shifting pattern of route awards observed in this study suggests that these early challenges did not result in abandonment of the scheme's mission but instead appear to have initiated a learning and improvement process. Rather than opening access indiscriminately, further rounds of UDAN route awards now look more strategic and confident in balancing regional coverage with the imperatives of sustaining new routes.

In referencing the shaping of awarded routes as a surrogacy indicator of government confidence, this study brings new insight to common judgments of UDAN, whose earlier measurements have tended to be in terms of operational feasibility or demand. It indicates that intent — as encoded in programmatic decisions — can itself evolve meaningfully over time, even without complete operational success. But one shortcoming of this approach is that it measures strategic intent and not outcomes realized. Without being privy to comprehensive post-award operational information, it is not possible to know how many of these Mission-Aligned tracks ultimately became commercially sustainable or sustained passenger demand. Future research could build on this study by tracking the operational life of successful routes, analyzing how initial confidence was translated into long-term success or failure across India's evolving regional air network.

Furthermore, the increasing share of Mission-Aligned routes across UDAN rounds carries important implications for future iterations of the scheme and for regional connectivity policy more broadly. The upward trend suggests that stakeholders have progressively refined their understanding of how to balance regional inclusion with network sustainability. Future UDAN rounds could build on this trajectory by embedding clearer evaluation frameworks that link route selection with measurable social and economic outcomes. More consistent post-award data collection, specifically on factors such as passenger demand, subsidy dependence, and route longevity, would allow the government to better calibrate incentives and identify which types of connections generate the greatest long-term regional impact. Beyond UDAN, these findings highlight the value of iterative policy design for large-scale public programs. As governments pursue similar connectivity initiatives in aviation, rail, or digital infrastructure, adopting a learning-based approach that continually aligns implementation choices with original equity goals can enhance both efficiency and developmental reach.

### Limitations

While this study provides insight into the evolution of government confidence in the UDAN scheme, it is constrained by the limits of publicly available data. The Airports Authority of India releases detailed route award lists for each UDAN round, but many important complementary datasets are not accessible to the public. Information such as the specific subsidy amounts allocated per route, the duration and renewal terms of those subsidies, and the operational status of routes over time is either incomplete or unpublished. While partial amounts of such data may be publicly accessible, specifically airline-specific data voluntarily submitted to the Standard Schedules Information Manual ("SSIM"), the vast majority of smaller airlines do not voluntarily submit information to such centralized locations. Thus, the absence of this data restricts the ability to evaluate the financial or operational outcomes associated with each route and limits the analysis to government intent as expressed through route allocation patterns.

Similarly, post-award monitoring data, such as passenger load factors, route profitability, cancellation rates, or airport utilization statistics, are neither systematically released publicly by airlines nor to the SSIM. These data would allow for a fuller understanding of how initial government confidence translated into long-term operational success or failure. Without access to such information, this study cannot assess whether Mission-Aligned routes sustained operations, achieved financial independence, or advanced regional equity outcomes beyond their initial designation.

Despite these limitations, the publicly available UDAN route data remain a valuable and legitimate basis for analyzing the evolution of strategic intent within the program. By focusing on route award patterns rather than post-operational results, the study offers a replicable and policy-relevant lens through which to understand how large-scale government initiatives mature over multiple phases of implementation.

### Conclusions

This study examined the evolution of government confidence in India's UDAN scheme through tracking the percentage of route awards that fell in line with the program's early regional equity objectives. Using a systematic classification of city sizes and statistically testing trends across five large UDAN rounds, the findings affirm the hypothesis that government confidence in the scheme evolved over time. A growing share of assigned routes prioritized connections among unserved communities and more heavily populated urban areas, indicative of rising strategic sophistication as the program aged.

The conclusions of this study offer more aggregate observations on how public programs develop in implementation. Even amid the challenges of operating and initial opprobrium, the UDAN scheme demonstrates that repeated rounds of policymaking can sharpen institutional intent to fundamental goals. Through examination of the design of successful routes as distinct from outcomes after operation, this study suggests that programmatic intention itself is a central—and measurable—dimension of public sector formation.

Future research could expand on this by integrating performance metrics regarding operations, measuring not only whether approved routes contributed to mission objectives but whether they remained viable in practice. Tracking route sustainability, passenger uptake rates, and economic effects locally would further develop the way early confidence resulted in long-term success in regional aviation within India.

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