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Dry Needling Intervention in Treating Musculoskeletal Disorders: A Scoping Review

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ABSTRACT

Dry Needling (DN) has emerged as an effective treatment for various musculoskeletal disorders (MSDs), although the specifics of its application and the range of treated disorders remain unclear. The objective is to map and summarise dry needling practices from a global perspective. This scoping review employs the Joanna Briggs Institute technique, utilising the PCC framework (Participants, Concept, Context) to establish eligibility criteria based on the PRISMA Scoping Review checklist. Searches in PubMed, PEDro, and Google Scholar aim to identify evidence on dry needling, either as a standalone intervention or combined with other treatments, with clinical outcomes such as short-term or long-term effects on pain and physical function. The review includes systematic reviews, RCTs, meta-analyses, literature reviews, and quasi-experimental studies. DN, widely adopted in Europe and gaining traction in North America and Asia, effectively addresses MSDs like myofascial pain syndrome, knee osteoarthritis, and patellofemoral pain syndrome. Studies highlight DN's effectiveness in reducing pain and enhancing muscle function. Further research, incorporating extended follow-up periods of 6 months to 1 year, is crucial to comprehensively evaluate DN's long-term impact on pain, functionality, and overall quality of life.

Keywords: physical therapy, musculoskeletal disorder, ultrasound-guided dry needling, dry needling techniques, global perspective.

1. Introduction

Musculoskeletal disorders (MSDs) pose a significant and complex challenge in healthcare, affecting patient well-being and straining global healthcare systems. According to a new review of Global Burden of Disease (GBD) 2019 data, over 1.71 billion individuals worldwide suffer from musculoskeletal diseases such as low back pain, neck discomfort, fractures, osteoarthritis, amputation, and rheumatoid arthritis. While the prevalence of musculoskeletal problems varies with age and diagnosis, it affects people of all ages all over the world. High-income countries are the most affected (441 million people), followed by countries in the WHO Western Pacific Region (427 million) and South-East Asia Region (369 million). Musculoskeletal diseases are also the leading cause of years lived with disability (YLDs), accounting for approximately 149 million YLDs, or 17% of all YLDs worldwide. In recent years, the therapeutic practice of dry needling (DN) has emerged as a promising solution for mitigating pain and enhancing functionality in individuals grappling with diverse MSDs. According to the American Physical Therapy Association (APTA), Dry needling involves the precise insertion of thin filiform needles beneath the skin's surface, targeting myofascial trigger points, musculature, and connective tissues. APTA supports the inclusion of dry needling in regulatory frameworks, accompanied by appropriate educational qualifications for PTs to engage in the intervention. This technique, endorsed by reputable organizations such as the American Physical Therapy Association (APTA), has gained traction owing to its minimally invasive nature and potential effectiveness in addressing the fundamental causes of musculoskeletal pain and dysfunction. In-depth examination of the current state of dry needling worldwide is presented in this publication, which also explores its uses, effectiveness, underlying mechanisms, and practical consequences in various therapeutic contexts worldwide. There will be a special focus on revealing how dry needling is utilized to treat a variety of MSDs, such as myofascial pain syndrome, patellofemoral pain syndrome, and knee osteoarthritis. Through a thorough analysis of a wide range of literature, including primary research studies, meta-analyses, and systematic reviews, our goal is to reveal the complex ways that dry needling is applied around the world to treat these conditions effectively. The researchers' goal in doing this study is to further our understanding of the critical role that dry needling plays in the worldwide management of MSDs.

2. Materials and Methods

This scoping review was conducted by using the Joanna Briggs Institute technique. It utilised the PCC framework (Participants = studies that utilise DN in the treatment of various MSDs with at least one session of DN and outcome measures (pain, functionality, QOL), Concept = dry needling intervention in physical therapy practice in the management of musculoskeletal disorders such as its techniques and methods, short-term and long-term effects based on their pain and functional outcomes. Context = articles in a clinical (effects) and geographical context (integration of DN in global perspective) to establish its eligibility criteria, which is based on the PRISMA Scoping Review checklist. The researchers provided inclusion and exclusion criteria to determine the extent of the articles that were used for the study.

2. 1. Eligibility Criteria

The gathered studies were eligible if they met the following criteria provided by the researchers. The inclusion criteria encompass studies involving (1) participants ages 12-65 years old, (2) studies which uses dry needling for musculoskeletal disorders (neck pain, shoulder pain syndrome, myofascial pain syndrome, spine disorders, tendinopathy, low back pain, knee & hip oa, plantar heel pain), with measurement of pain and functional outcomes (VAS: Visual Analog Scale; NPRS: Numeric Pain Rating Scale; NDI: Neck Disability Index; KOOS: Knee Injury and Osteoarthritis Outcome Score; PKE: Passive Knee Extension; FFD: Finger-floor distance; WOMAC: Western Ontario and McMaster; DASH: Disability of the Arm, Shoulder, and Hand; SPADI: Shoulder Pain and Disability Index; ODI: Oswestry Disability Index: PSFS: Patient Specific Functional Scale; FHSQ: Foot Health Status Questionnaire) and (4) examination of short-term and long-term effects. Exclusion criteria involve

(1) studies using wet needling which involves injecting medicinal liquids like corticosteroids and anaesthetics into muscles, ligaments, tendons and scar tissue, (2) acupuncture which is based on meridians and qi principles, (3) participants with neurological disorders or underlying medical conditions (such as asthma, cancer, cerebrovascular diseases, and diabetes mellitus), and (4) studies that are not freely accessible.

2. 2. Search Strategy

The primary data were sourced from the English-language literature. They included systematic reviews, randomized controlled trials, meta-analysis papers, review articles and quasi-experimental studies that addressed the key research questions posed. The improvement framework proposed by Peters et al. guided the review process, alongside Arksey and O'Malley's methodological approach, which involved identifying the research question, selecting and identifying relevant studies, charting the data, synthesizing, summarizing, and reporting the findings, and consulting with stakeholders interested in the outcomes for validation.

Search strategy: A comprehensive search using a three-step Joanna Briggs Institute (JBI) search strategy was initially implemented in the PubMed, PEDro and Google Scholar databases, using the appropriate type of terms found in titles, abstracts or as keywords. To provide the highest level of evidence (HLE) possible, all full-text articles that met the inclusion criteria were screened, with a focus on papers published from 2018 onwards. The following searches rested on Medical Subject Headings (MeSH) terms—"Dry Needling," "Musculoskeletal Disorder," and "Physical Therapy Practice"—to demarcate them from other studies that did not meet the inclusion and exclusion criteria.

The initial search process yielded 120 records. A total of 45 articles from PubMed, 20 from PEDro, and 10 from Google Scholar were identified after applying the inclusion and exclusion criteria. After a thorough inspection, 38 papers were ultimately deemed eligible for the final research.

2. 3. Selection Process

The researchers utilized the JBI System for the Unified Management, Assessment, and Review of Information (SUMARI). These guidelines guide all stages of a systematic review or scoping review, including search development and best practices for review methods, data extraction, and data analysis, to lower the risk of error and bias in the review process. In addition to these guides, standards exist to improve systematic review reporting, such as the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), which specifies a minimal set of needed items. JBI developed the System for the Unified Management, Assessment, and Review of Information (SUMARI) to guide researchers through the complete systematic review process, based on one of these manuals.

2. 4. Data Collection Process

Two independent reviewers performed extraction, and a third reviewer ensured the completeness of information. The extracted data included the author(s), year of study publication, basic demographic information, disease model (type of musculoskeletal disorder and targeted anatomic region/body area), treatment approach (dry needling point, soft tissue treated, location, and nature of comparator therapies administered), outcome assessments conducted (informed by specific diagnostics employed), duration and time points measured at follow-up, and main findings reported.

2. 5. Characteristics of Included Studies

Distribution of study types in 38 included studies and English-speaking countries showed that the majority were RCTs (55%), followed by systematic reviews with an accompanying range (17.5%) and other designs (27.5%). This highlights the need for

further experimental research approaches to provide better evidence for the therapeutic effects of dry needling. More medically reviewed studies originated from Asia (30%) and Europe (40%) compared to North America (25%). Therefore, continental distribution may potentially have influenced the number of audits included in our sample. A whopping 95% of studies (intercept=−0.01, test statistics = 0.0022; $p < 0.0001$) gathered by the investigators primarily dealt with musculoskeletal disorders that involve dry needling in their intervention component. Among the MSDs reviewed, MPS was the most frequently studied, accounting for 26% of cases combined with DNI, while patellofemoral pain syndrome and headache each accounted for 4% of combined use. According to the distribution of interventions, dry needle alone was evaluated in most included studies (70%), while the remaining studies investigated its combination with other interventions, such as hard block and dry needling groups.

2. 6. Appraisal of Included Studies

Reviewers used the JBI Sumari tool to appraise the collected studies. The tool offers a wide array of critical appraisal instruments for researchers looking to check the methodological shortcomings of the study. JBI Sumari has sections that are presented as a series of questions in a study-specific checklist. Duplicates were first removed from the collected articles, after which two authors screened the titles and abstracts of these articles for potential eligibility. Next, the full texts of all potentially eligible studies were analyzed for eligibility. Two reviewers had to reach an agreement on inclusion and exclusion, and the review of a third party resolved any disagreement arising between the two reviewers to determine article inclusion. Eligible articles were then reviewed independently by two reviewers (AW, SR). One reviewer initially assessed the articles, and the studies were appraised once more by a second reviewer to prevent potential bias. Finally, the senior reviewer then performed a secondary review to make the final decision on whether to include or exclude articles.

3. Results

3. 1. Mapping of Extracted Data

The authors were able to gather the commonly used dry needling techniques employed as an intervention in the treatment of musculoskeletal disorders. These techniques include dry needling combined with the use of manual therapy, dry needling with the use of modalities (US and electrical nerve stimulation), and dry needling alone (trigger point dry needling, superficial and deep dry needling, and dry needling with trigger point compression) (see Supplementary Materials: Table 1).

3. 2. Nature of Dry Needling

Dry needling without other interventions is found to be the most common dry needling intervention in terms of treating musculoskeletal disorders. It is most evident that dry needling without any other intervention (45%) shows positive results in pain reduction, pain-related disability, and pressure pain threshold in the short term when compared to sham and no needling treatments. However, it can be enhanced when combined with other modalities and interventions such as manual therapy (MT) or exercise therapy (ET) (see Supplementary Materials: Table 2).

3. 3. Integration of Dry Needling in a Continental Perspective

The integration of dry needling in Eastern Continent (Europe and Asia) was measured in 29 studies with 17 studies from Europe (15 studies from Spain and 2 studies from Belgium) 12 studies from Asia (6 studies from Iran, 2 studies from Israel, 2 studies from Pakistan, 1 study from Cyprus and 1 study from Saudi Arabia) All of the studies included RCT, systematic review, case series, quasi-experimental study, and prospective questionnaire. 17 out of 38 articles (42.5%) originate from Europe, 4 out of 17 (23.5%) treated myofascial pain syndrome (MPS) using trigger point dry needling (TrpDN) and DN with percutaneous

nerve stimulation. Concurrently, the integration of dry needling in Western Continent (North America and South America) was mapped in 10 studies (6 RCT, 1 case series, 1 quasi-experimental, and 1 prospective questionnaire from the United States and 1 RCT from Brazil). 9 out of 38 (22.5%) articles originate from North America. 2 (5%) out of 9 treated LBP using Dry Needling (DN). (see supplementary materials: Table 3).

3. 4. MSD Commonly Treated Using Dry Needling

Based on the collected data, we learnt that myofascial pain syndrome (MPS), specifically cervicalgia, was the most frequently managed musculoskeletal pathology. Some studies emphasise the role of dry needling interventions in MPS, showing successful outcomes in pain intensity, pain-related disability, pressure pain thresholds (PPT), and cervical range of motion (ROM). These studies were conducted across continents, with significant representation in Europe (especially Spain), followed by North America, Asia, and South America. The interventions usually included dry needling techniques applied to trigger points or myofascial regions, either alone or combined with other treatment modalities like percutaneous electrical nerve stimulation or ultrasound guidance. Standard outcome measures used for evaluating the effectiveness of dry needling include visual analogue scales (VAS)/numeric pain rating scales (NPRS), pressure pain thresholds (PPTs) retest methods, disability measurements (e.g., Neck Disability Index; Quick Disabilities of the Arm, Shoulder and Hand Questionnaire/Shoulder Pain and Disability Index), range of motion measures, and patient-reported outcomes that are not specific to any given region treated with the dry needling (e.g., SF-36/DASH). In general, the numerous studies demonstrating positive outcomes for dry needling in reducing pain and improving function across various musculoskeletal conditions highlight its potential as an effective treatment modality for MPS and associated syndromes (see Supplementary Materials: Table 4).

3. 5. Synthesis of Results

Dry needling interventions for musculoskeletal disorders have been extensively studied across various continents, including Europe (Spain), North America (USA), Asia (Iran, Israel, Pakistan, Saudi Arabia), and South America (Brazil). These studies, comprising a mix of randomized controlled trials (RCTs), systematic reviews, meta-analyses, scoping reviews, cohort studies, pilot studies, and quasi-experimental studies, have focused on a range of conditions such as neck pain, myofascial pain syndrome (MPS), spine disorders, shoulder pain, subacromial syndrome, tendinopathy, upper trapezius myofascial pain syndrome, plantar fasciitis, patellar tendonitis, knee osteoarthritis (KOA), chronic tension-type headache, hip osteoarthritis (OA), chronic nonspecific low back pain (LBP), lower extremity myofascial trigger points, acute golfer's elbow disability, and gluteus medius strength measurements. These interventions, including dry needling, dry needling with percutaneous electrical nerve stimulation, ultrasound-guided dry needling, electrical dry needling, and trigger point dry needling, have been evaluated using various outcome measures such as the visual analog scale (VAS), pressure pain threshold (PPT), neck disability index (NDI), numeric rating scale (NRS), goniometer, Disabilities of the Arm, Shoulder, and Hand (DASH), Quick Disabilities of the Arm, Shoulder, and Hand (Q-DASH), neck pain and disability scale (NPDS), neck pain and disability scale (NPQ), Short Form-36 (SF-36), foot health status questionnaire (FHSQ), quality of life (QOL), Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), Roland-Morris Disability Questionnaire (RMDQ), Oswestry Disability Index (ODI), quick disabilities of the arm, shoulder, and hand (Q-DASH), knee injury and osteoarthritis outcome score (KOOS), and Victorian Institute of Sport Assessment-Patella (VISA-P). Overall, the effectiveness of dry needling has shown variability across studies, demonstrating positive outcomes in reducing pain intensity, improving functional parameters, increasing pressure pain thresholds, and enhancing range of motion. However, further research is warranted to determine the long-term efficacy and optimal application of dry needling in the management of various musculoskeletal disorders.

3. 5. 1. Utilization of Dry Needling Techniques

The utilization of dry needling was done by varieties of dry needling techniques for musculoskeletal disorders which includes trigger point dry needling, electrical dry needling, ultrasound guided dry needling, and superficial and deep dry needling. The use of trigger point dry needling showed significant pain reductions on patients with patellofemoral pain syndrome, mps in the neck and upper back. Although, according to a systematic review study from Spain, there is low to moderate evidence that supports a positive effect of trigger point dry needling on pain and related impairment in patellofemoral pain, but not on knee osteoarthritis (OA) or postoperative pain, in the short term (Rahou-El-Bachiri et al., 2020). The use of electrical dry needling showed positive effects in pain reduction of chronic low back pain. However, there is a lack of standardisation in terms of the length of the analgesic effect and the necessary dose. Additionally, ultrasound-guided DN of the patellar tendon in combination with conventional physical therapy (CPT) reduced pain, improved function, and showed a tendency to decrease tendon thickness in patients with patellar tendinopathy. One study from Iran examined the effects of using shallow and deep dry needling procedures on the range of motion and functional capacity of the neck. However, the deep dry needling patients experienced more noticeable and significant changes. Moreover, dry needling combined with manual therapy and exercise was utilized in treating musculoskeletal disorders.

Dry needling combined with other therapies may have a favorable short-term impact on pain intensity, pain-related disability, pressure pain thresholds, and cervical range of motion in patients with neck pain linked to TrPs, according to low-to-moderate evidence (Fernández-De-Las-Peñas et al., 2021). Both short-term and long-term impacts were undetectable. Incorporating electrical dry needling into a manual therapy (MT) and exercise regimen was more effective than MT and exercise alone in relieving pain, improving function, and reducing related disability. A study involving patients with plantar fasciitis who received electrical dry needling in addition to manual treatment, exercise, and ultrasound showed considerable improvement, outperforming those who received manual therapy, exercise, and ultrasound alone (Dunning, Butts, Young, et al., 2018).

3. 5. 2. Head and Neck

An RCT study from Asia showed that in individuals with persistent tension-type headaches, trigger point dry needling reduces headache severity, frequency, and duration while also improving health-related quality of life. Two RCT studies from Europe and Asia use trigger point dry needling (TrP-DN) as the main intervention for neck pain and chronic neck pain (Gildir et al., 2019). According to a study from Spain that used TrP-DN, when performed on a trigger point, latent trigger point, or non-trigger point area, deep dry needling of the trapezius muscle has the same positive effects on reducing pain intensity, discomfort, and local mechanical hyperalgesia (Martín-Sacristán et al., 2022) .

Another study from Saudi Arabia found that TrP-DN plus exercise had similar effects on pain, depression, and quality of life at the end of a two-week follow-up period (Almushahhim et al., 2022). One systematic review from Europe uses dry needling for neck pain. The study which originated from Spain showed that dry needling can be used as a treatment option for chronic neck pain. According to the study that was analysed, successful outcomes were obtained in the near term and during the three to six month follow-up period. However, since it only persisted for a year, the long-term effects were found to be limited (Rodríguez-Huguet et al., 2022).

An RCT study from Spain shows DN can be effective for improving neck pain intensity and related disability when compared with a comparative group immediately after and at short but not at mid term follow ups in people with myofascial TrPS associated with neck pain symptoms (Navarro-Santana et al., 2020). Additionally, One RCT study from Spain can be effective for improving neck pain intensity and related disability when compared with a comparative group immediately after and at short but not at mid term follow ups in people with myofascial TrPS associated with neck pain symptoms (Navarro-Santana et al., 2020).

3. 5. 3. Upper Extremities

The effectiveness of DN when combined with conventional physical therapy in the recovery of patients with subacromial syndrome (SAS) of non-traumatic origin for at least three months and had at least four points on VAS and clinically diagnosed with subacromial pain syndrome (SAPS) and found out that DN is effective and safe in reducing the pain and disability produced by SAS, with the best combination of treatment turning out to be conventional physical therapy together with DN, obtaining more stable and longer-lasting benefits than merely applying the techniques in isolation (Blanco-Diaz et al., 2022).

A case series observed the use of DN in conjunction with exercise as a management strategy for patients who meet the clinical diagnostic criteria of SAPS to assess the short and intermediate-term effects of DN in conjunction with exercise. 25 patients met the criteria of SAPS and were given DN treatment first in isolation to observe the immediate effects of DN and exercises were given on their third visit. Results show significant improvement on patients Q-DASH, NPRS, GROC and improvement on ROM at 3 months follow-up. The case series encourages the use of DN in conjunction with exercise therapy in the management of SAPS (Morgan et al., 2019).

1 case report from Iran assessed the acute effects of one session of DN on a patient with a golfer's elbow. A 40-yr old retired male athlete reported an acute pain on the medial side of elbow and was given one session of deep-dry needling on his flexor area (medial epicondyle) and on the inner side of his elbow which lasted for 20 minutes. Results showed no improvements in his range of motion or pain immediately following dry needling. After two days, patient reported reduced pain and being able to do more activities functionally related with the elbow, his movements had improved, and there was no specific movement limitation. At the seven-day follow-up, the patient was able to undertake exercise training with elastic bands without pain (Shariat et al., 2018).

One RCT assessed the effectiveness of Trigger Point Dry Needling (Trp-DN) in sixty-six patients aged 65 years and older with trigger points in the ipsilateral infraspinatus of the painful shoulder with latent MTrP group (pain when compressed) and active MTrP group (pain upon movement) and found out that dry Needling on the ipsilateral infraspinatus showed significant pain reduction, increased pressure pain threshold but no significant improvement on grip strength (Calvo-Lobo et al., 2018).

3. 5. 4. Paralumbar Area

A study from the USA has said that Dry needling appears to reduce resting erector spinae muscle following treatment of patients with low back pain. Therefore, the authors recommended that providers should consider the use of dry needling when patients exhibit aberrant stiffness of the lumbar muscles. Numerical Pain Rating Scale (NPRS) and Oswestry Disability Index (ODI) were used as the outcome measures for the intervention (Koppenhaver et al., 2022). Another RCT study from the USA indicated no between-group differences between patients experiencing non-specific LBP who received a semi-standardized non-thrust manipulation (NTM) or a segmental and distal DN approach without needle manipulation. NPRS, ODI, Patient Specific Functional Scale (PSFS) and Pressure Pain Threshold (PPT) were used by the authors as the outcome measure for the non-specific LBP (Griswold et al., 2019). One Pilot Study from Iran has said that a single session of deep DN improved pain and function and increased hamstring flexibility. The study supports the use of DN in patients with LBP and hamstring tightness. VAS, PKE, FFD test, and FRI were used as the outcome measure for this study (Bazzaz-Yamchi et al., 2021).

3. 5. 5. Lower Extremities

The use of dry needling as an intervention in treating hip osteoarthritis (OA) is evident in Europe. A Systematic Review study from Spain shows that for patients with hip OA, there is extremely low-quality evidence that DN has a favourable effect in the short term on pain severity and physical function. The study's outcome metric was pain intensity. However, more research must be done to evaluate the medium and long-term effects (Jimenez-del-Barrio et al., 2022). An RCT study from North

America/USA assessed the effects of ultrasounded DN compared to DN alone in the management of painful knee osteoarthritis (KOA). US-guided DN with exercise therapy may be more effective than traditional DN with exercise therapy or exercise therapy alone in reducing pain of KOA due to accuracy offered by ultrasound by pin-pointing painful trigger points, VAS and KOOS subscales were used as outcome measures (Pang et al., 2022).

One SR from Europe/Spain investigated the effect of DN in the management of KOA. Very low-quality evidence suggests a positive effect of DN for reducing pain intensity and improving physical function in the short term in patients with osteoarthritis. Further investigation is needed to determine medium- and long-term effects (Jimenez-del-Barrio et al., 2022). One SR from Europe/Spain also evaluated the effects of DN in knee pain syndrome. Low to moderate evidence suggests a positive effect of trigger point dry needling on pain and related disability in patellofemoral pain, but not knee osteoarthritis or post-surgery knee pain, at short-term. More high-quality trials investigating long-term effects are clearly needed (Rahou-El-Bachiri et al., 2020).. Furthermore, individuals who received the combination of electrical dry needling, MT, and exercise improved much more than those who received MT and exercise alone at 6 weeks and 3 months. At 3 months, patients who received electrical dry needling were 1.7 times more likely than those who received MT and exercise to have completely stopped taking pain medication. Additionally, more patients in the dry needling group achieved a successful outcome than those in the MT and exercise group. At 3 months, the effect sizes were high in favour of the electrical dry needling group for all outcome measures (Western Ontario and McMaster Universities (WOMAC) Osteoarthritis Index). Incorporating electrical dry needling into an MT and exercise regimen was more successful than MT and exercise alone in relieving pain, function, and related-disability.

4. Discussion

A search of the literature provided 38 studies that met the inclusion criteria for this scoping review. This resulted in dividing the studies based on their origin of the continent from western and eastern, dry needling techniques and methods on musculoskeletal disorders.

According to the data that we reviewed from Asia about dry needling, only 12 out of 38 (30%) claim the integration of DN in Asia (See Table 1). Geographically speaking, most of the countries that were included from Asia were close to the Western Countries. It can be said that they are mostly influenced by the western practice. It should also be noted that there are few local literatures in regards to the utilization of dry needling as intervention for musculoskeletal disorder. 17 out of 38 (42.5%) included studies have shown the integration of DN in Europe. DN is already established as a part of physical therapy practice mostly in Spain. 10 out of 38 (25%) included studies were found from North America. There are limited studies about dry needling intervention for musculoskeletal disorders from South America with a total of 1 out of 38 (2.5%) included studies.

Dry Needling (DN) is being widely utilised globally as an intervention for pain reduction and improvement of function for patients with musculoskeletal disorders. There is no superiority of DN over other treatments (manual therapy or exercise or physical agent and modality). Although, DN combined with other PT interventions shows improved outcome in patients with MSD's. Multiple DN techniques and methods were used in treating MSD's. Among all of the techniques that were used, DN and TrP-DN showed the most significant improvement in reducing pain for patients with MSD's. Additionally, ultrasound-guided dry needling was found to be more effective compared to traditional DN with exercise therapy or exercise therapy alone when it comes to reducing the pain of patients with knee osteoarthritis (KOA). For the electrical DN, although it has been proven to be effective in reducing pain; the duration of the analgesic effect and the dose required are contradictory. Consequently, electrical dry needling added with manual treatment, exercise, and ultrasound is more effective than manual therapy, exercise, and ultrasound alone.

Accordingly, in this scoping review, musculoskeletal disorders that are often treated include the following: acute and chronic MPS, chronic neck pain, spine disorders, subacromial pain syndrome, shoulder pain, tendinopathies, golfer's elbow, chronic tension-type headache, LBP, Plantar heel pain, knee OA, hip OA, gluteus medius, plantar fasciitis and patellar tendonitis. Almost

all the studies have shown a positive and significant improvement at all domains at short-term (3 weeks follow-up) but there is a need for a longer follow-up to conclude the long-term effects of DN in the treatment of MSD's and multiple studies have recommended that more high quality trials are needed. The MSD's were measured based on their pain and functional outcomes that were assessed using PPT, VAS, NPRS, NDI, KOOS, PKE, FFD, WOMAC, DASH, SPADI, ODI, PSFS, and FHSQ. Dry needling is an invasive treatment but there are minimal to no adverse events reported in the studies. Minor adverse events reported include mild bleeding, bruising, and pain. Overall, the risk of major adverse events to happen during DN is small. In terms of cost, DN is considered cost-effective in the treatment of various MSD. Although other interventions such as percutaneous needle electrolysis may be more cost-effective than DN in the long run. DN is now being considered as a viable treatment for athletes with musculoskeletal problems for improving grip strength by applying DN in the teres major mm. According to the study of Laita et. al, after a single session of DN in active MTrPS of the teres major mm in handball athletes with shoulder pain, the pain during the throwing action decreased, the glenohumeral internal rotation ROM increased and the extensibility was improved. In addition, we have found out that DN can also be used in reducing lumbar muscle stiffness in patients suffering with LBP.

5. Conclusion

Dry needling is widely used on the European continent, and it is found to be an emerging invasive intervention in North America and Asia. There are limited studies that originate in South America about dry needling. The use of dry needling has been primarily associated with treating myofascial pain syndrome (MPS), knee disorders such as knee osteoarthritis and patellofemoral pain syndrome and shoulder pain. Dry needling alone has been shown to be effective in reducing pain and improving muscle function in various studies. However, the effectiveness of dry needling can be enhanced when combined with other modalities and interventions such as manual therapy (MT) or exercise therapy (ET), depending on the specific condition being treated. Moreover, dry needling is proven to be effective in reducing pain in the short term; nonetheless, more intensive studies are needed that include longer follow-up periods to analyse its long-term effects.

6. Strengths and Limitations

The findings of this scoping review should be considered in light of its inherent strengths and limitations. Among its strengths are a broad and comprehensive literature search, adherence to methodological rigour, systematic data extraction, and the inclusion of a diverse range of study designs—including systematic reviews (SRs), randomised controlled trials (RCTs), experimental studies, case reports, and case series. However, the review is not without limitations. One key limitation is the reliance on a relatively small number of locally conducted studies, which may affect the generalisability of the results. Furthermore, while dry needling appears promising, there is a need for greater standardisation in the application of combined therapeutic modalities. Additional research is also warranted to explore its effectiveness in managing a wider range of musculoskeletal disorders (MSDs), such as post-arthroplasty conditions, fractures, and osteoporosis.

7. Recommendations

To further develop this study, the investigators recommended that future researchers should conduct experimental trials regarding the utilisation of DN as an intervention for MSDs which were not included in this study and also include longer follow-up periods, ranging from 6 months to 1 year, to determine the long-term effects of DN in pain reduction, functionality, and overall improvement of QOL. Future researchers should also investigate the integration of dry needling in local physical therapy practice.

Supplementary Materials

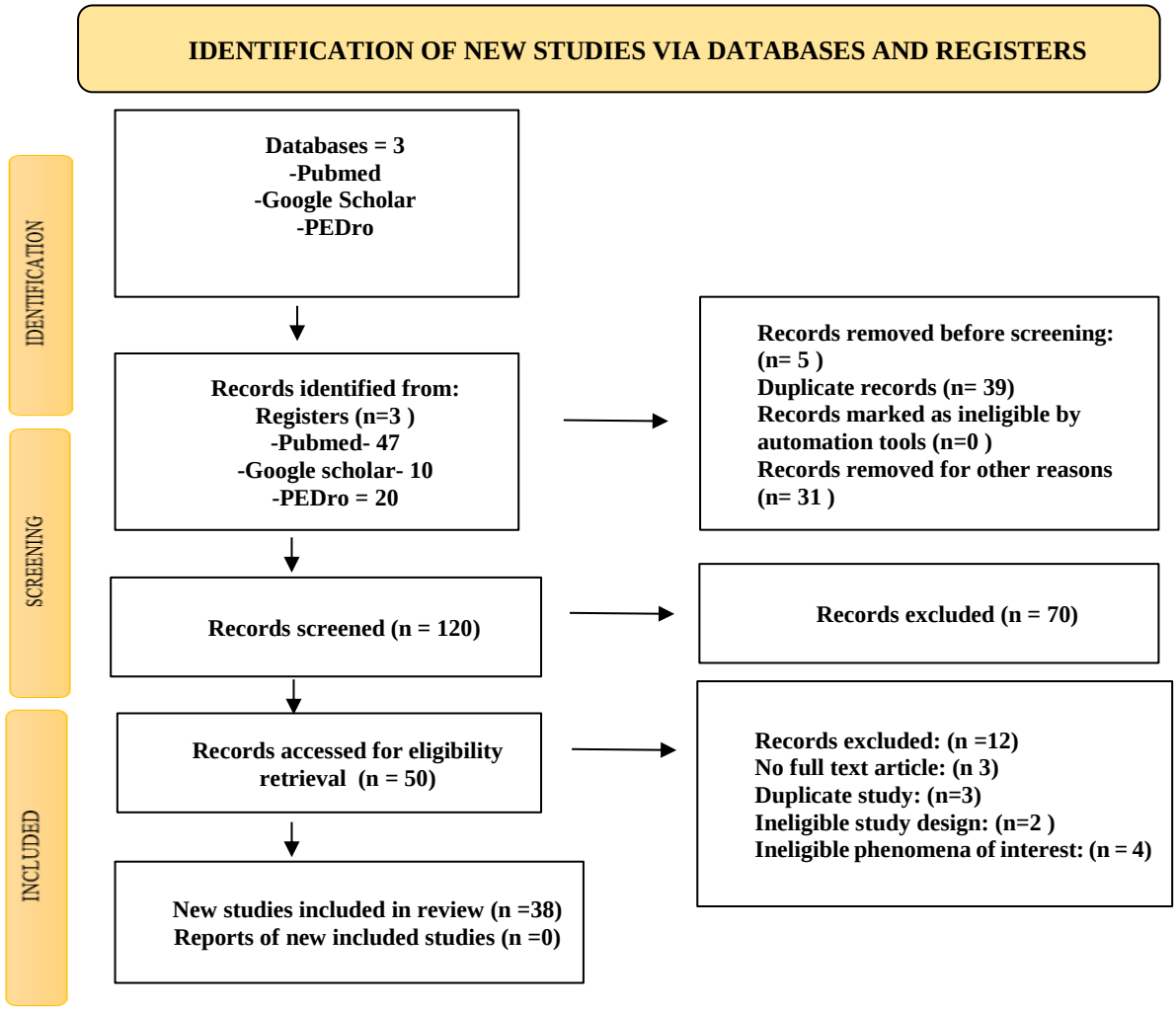

Figure 1. PRISMA-ScR flow diagram for scoping review process.

Table 1. Study Characteristics of Included Reviews

Characteristic		
Study Design	**N = 38**	**Percentage (%)**
systematic review	7	17.5%
RCT	21	55%
Other study design	10	27.5%
Year Published		
2018	7	17.5%
2019	6	15%
2020	7	18.4%
2021	8	21%
2021	9	22.5%
2022	1	2.5%
2023	7	17.5%
Continent		
North America	10	25%
South America	1	2.5%
Europe	17	42.5%
Asia	12	30%
MSD		
Headache	1	4%

Chronic Neck pain	2	9%
MPS	6	26%
Shoulder Pain	3	13%
Spine Disorders	1	4%
Golfer's Elbow	1	4%
Low Back Pain	2	9%
Hip Osteoarthritis	2	9%
Knee Osteoarthritis	5	22%
Patellofemoral Pain Syndrome	1	4%
Plantar Fasciitis	3	4%
Interventions		
dry needling alone	26	68 %
dry needling with other intervention	12	30 %

Table 2. Tabulation of Different Dry Needling Techniques

Dry needling techniques	N	% out of 38
dry needling	17	45 %
dry needling trigger point	9	24 %
ultrasound-guided dry needling	3	8 %
dry needling with percutaneous electrical nerve stimulation	2	5 %
superficial and deep dry needling	2	5 %
electrical dry needling	2	5 %
dry needling trigger point with manual therapy	1	3 %
dry needling and trigger point compression	1	3 %
periosteal electrical dry needling with manual therapy	1	3 %

Table 3. Geographic Distribution of Dry Needling

Geographic Distribution of Dry Needling	N = 38	% out of 38	Most Used Dry Needling Technique	N of studies of said technique
Europe	16	42.5	dry needling	12
Asia	12	30	dry needling	7
North America	9	25	dry needling	6
South America	1	2.5	dry needling	1

Table 4. Tabulation of Musculoskeletal Disorders Commonly Treated Using Dry Needling

MSD	N=38	% out of 38
Mps	9	24 %
Knee region	8	21%
Shoulder pain	6	16%
Neck pain	4	10%
Hip region	3	8%
Low back pain	3	8%
Ankle region	2	5%
Spine disorder	1	3%
Headache	1	3%
Elbow	1	3%

Table 5. Utilization of Dry Needling in Global Perspective

Ref	Study Design	Continent/ Country	MSD	Intervention	Outcome Measure	Results
(Martín-Sacristán et al., 2022)	RCT	Europe/ Spain	neck pain	dry needling trigger point	Visual Analog Scale (VAS), Pressure pain threshold (PPT) and Neck Disability Index (NDI)	Deep dry needling of the trapezius muscle, regardless of whether it is on a trigger point, latent or non-trigger point area produces the same positive effects in improving pain intensity, discomfort and local mechanical hyperalgesia.
(Fernández-De-Las-Peñas et al., 2021)	Systematic Review and Meta-Analysis	Europe/ Spain	MPS	dry needling	pain intensity, pain-related disability, PPT, and cervical ROM	There is a positive effect in the combination of dry needling with other interventions when improving pain intensity, pain related disability, pressure pain thresholds, and cervical ROM in people with neck pain associated trigger point at short-term.
(Fernández-Carnero, 2021)	RCT	Europe/ Spain	MPS	Dry needling with Percutaneous Electrical Nerve Stimulation	VAS and PPT	There is an improvement in both dry needling with percutaneous electrical nerve stimulation of high frequency and low frequency without any noticeable difference between the two.
(Funk & Frisina-Deyo, 2020)	Scoping review	North America/ USA	Spine Disorder	Dry Needling	VAS, PPT, ROM	There are many positive results in the cervical and thoracolumbar-pelvic region. Still, functional outcome tools best suited to tracking the outcomes of dry needling for spine related disorders must be explored.
(Ebrahimi Takamjani et al., 2020)	Systematic Review and Meta-Analysis	Asia/Iran	MPS	Ultrasound-guided dry needling	VAS, NPRS, Goniometer, NDI, DASH	US-Guided may help to treat patients with MPS. Almost all studies reported improvement of pain and functional outcomes at short-term but further RCT's with longer follow-up is needed to provide conclusive results.
(Calvo-Lobo et al., 2018)	RCT	Europe/ Spain	Shoulder Pain	Dry Needling	The Numeric Rating Scale, the pressure pain threshold	Dry Needling on the ipsilateral infraspinatus showed significant pain reduction, increased pressure pain threshold but no significant improvement on grip strength.

(Lew et al., 2021)	RCT	North America/ USA	MPS	Dry needling and trigger point manual therapy	VAS, NRS, PPT	This study was consistent with existing research that demonstrated the effectiveness of DN and TPMT in improving pain and function in the short to medium term for patients with myofascial pain syndrome in the neck and upper back.
(Chys et al., 2023)	Umbrella Review	Europe/ Belgium	MPS	Trigger Point Dry Needling	Risk of bias (RoB) was assessed with the AMSTAR-2 tool	Overall, several studies show that DN is superior to sham/ no intervention and equally effective to other interventions for pain reduction regardless of body region. Some SR favored WN more than DN in short term pain reduction. Limited Data for the medium and long term effects of DN. DN has a short term analgesic effect and may have an additional treatment effect when used as adjunct to other physiotherapeutic interventions compared to these interventions alone.
(Blanco-Diaz et al., 2022)	Systematic Review	Europe/ Spain	Subacromial Syndrome	Dry Needling	VAS, ROM, PPT, Functional with DASH and SPADI	DN has been demonstrated to be effective at reducing the pain and disability produced by SAPS, obtaining the best results in combination with conventional physiotherapy rather than as an isolated technique.
(Morgan et al., 2019)	Case Series	North America/ USA	Subacromial Pain	Dry Needling	Quick Disabilities of the Arm, Shoulder, and Hand (Q-DASH)	This case series provides insight to the observed short- and intermediate-term effects of dry needling combined with exercise for SAPS.
(Ezzati et al., 2018)	Quasi experimental study	Asia/Iran	MPS	Superficial and Deep Dry Needling	Neck Disability Index (NDI) instrument a goniometer	The changes in the range of motion and the functional ability of the neck were observed over time when superficial and deep dry needling techniques were used. However, these changes were more significant and prominent in patients treated with deep dry needling, especially in the follow-up periods.

(Stoychev et al., 2020)	Narrative Review	Asia/Israel	Tendinopathy	Dry Needling	patient-reported and objective findings	Current research provides initial support for the use of tendon dry needling as a stand-alone procedure for tendinopathy. It seems that it is a safe and effective treatment method, although there is a vast diversity regarding the technique of the needling, ultrasound guidance, and additional treatments used.
(Ziaeifar et al., 2019)	RCT	Asia/Iran	Trigger Point Upper Trapezius	Dry Needling and trigger point compression	Pain intensity, and neck, shoulder and arm disabilities	This study revealed that both DN and TPC produced three-month improvement in pain intensity and disability, therefore, could be a potential treatment for individuals with MTrPs in the UT muscle.
(Navarro-Santana et al., 2020)	RCT	Europe/ Spain	MPS	Dry Needling	pain intensity, pain-related disability, PPT and cervical ROM	Dry needling can be effective for improving neck pain intensity and related disability when compared with a comparative group immediately after and at short but not at mid term follow ups in people with myofascial TrPs associated with neck pain symptoms.
(Shariat et al., 2018)	Experimental study	Asia/Iran	Chronic Golfer's Elbow disability	Deep Dry needling	VAS	No changes in his range of motion and pain immediately after dry needling. 2 days follow-up, he reported less pain and was able to do more activities functionally associated with the elbow, movements were improved and there was no specific movement limitation. Seven days, follow-up, patient was able to do exercise training with elastic bands pain free.
(Ceballos-Laita et al., 2021)	RCT	Europe/ Spain	Teres Major	Dry Needling	NPRS, hand-held dynamometer, and inclinometer	A single session of DN in the teres major muscle was effective for improving pain intensity during throwing actions, internal rotation ROM and extensibility in HB athletes with shoulder pain.
(Almushahhim et al., 2022)	RCT	Asia/ Saudi Arabia	Chronic Neck Pain	Trigger point dry needling "fast-in, fast-out needle insertion" method	NPRS, NDI, SF-36 QOLS, and BDI	One session of trigger point dry needling with exercise and exercise alone showed the same pain and quality-of-life outcomes after a two-week intervention. The researchers did not recognize trigger point dry needling as an efficient intervention because there were

						inadequate high-quality studies on the subject and unavailable data on the minimum quantity of injections required for better dry needling outcomes in chronic mechanical neck pain patients.
(Rodríguez-Huguet et al., 2022)	Systematic Review	Europe/ Spain	Chronic Neck Pain	Dry Needling	VAS and NPRS, NDI, NPQ, PPT	Positive results were obtained in the short-term and during the follow-up conducted between three and six months, demonstrating that DN can be an effective therapy option for CNP. Additionally, this strategy may provide superior results to a placebo intervention based on the application of simulated DN.
(Gildir et al., 2019)	RCT	Asia/ Cyprus	Chronic Tension-Type Headache	Trigger Point Dry Needling	Headache intensity, frequency and duration of headache, and quality of life, assessed by the Short Form-36	After treatment, the intensity, frequency, and duration of headaches as well as the scores on the Short Form-36 subscales considerably decreased in the dry needling group (P .05). All the effect sizes for headache factors were large in the dry needling group.
(Pai et al., 2021)	RCT	South America/ Brazil	Shoulder pain	Trigger point Dry needling	NRS and quantitative sensory testing protocol	Dry needling group shows significant pain reduction compared to sham DN. In the active DN group alone, pain reduction scores were substantially different on the second day following needling and remained that way until the seventh day, along with improvements in other pain dimensions and a decrease in the area of mechanical hyperalgesia
(Yehoshua et al., 2022)	Cohort	Asia/Israel	MPS	Dry Needling	SF-MPQ	The study showed reductions in acute pain in all areas of the SF-MPQ 10 minutes and 1 week following DN completed by a GP. DN is a good therapeutic choice for GPs to help MPS patients.
(Khan et al., 2021)	Systematic Review	Asia/ Pakistan	MPS	Trigger point Dry needling	VAS, FHSQ, QOL	On the basis of the best evidence available, dry needling seemed to be effective in pain reduction related to lower extremity myofascial trigger points. Evidence also suggested that there was not much positive effect of myofascial trigger point dry needling on depression, anxiety,

						muscular strength and quality of life.
(Koppenhaver et al., 2022)	RCT	North America/ USA	LBP	Dry needling	NPRS, ODI	Dry needling appears to reduce resting erector spinae muscle following treatment of patients with LBP. Therefore, providers should consider the use of dry needling when patients exhibit aberrant stiffness of the lumbar muscles.
(Al-Boloushi et al., 2019)	RCT	North America/ USA	Plantar Heel Pain	Dry Needling and percutaneous needle electrolysis	Pain subscale of the Foot Health Status Questionnaire visual analogue scale	Plantar heel pain is a common cause of foot pain and discomfort affecting the health and quality of life of patients, with a high tendency for relapse and chronicity . Previous studies have demonstrated the positive effect of conservative treatment in reducing painful conditions associated to PHP, while other RCTs show that DN probably has a higher potential benefit over more conservative approaches
(Dunning, Butts, Young, et al., 2018)	RCT	Europe/ Spain	Knee OA	Periosteal Electrical Dry Needling and Manual therapy	Related disability WOMAC total score	At 3 months, patients who had electrical dry needling were 1.7 times more likely than those who received MT plus exercise to have totally ceased taking pain medication. Based on a threshold score of 5 on the global rating of change, considerably more patients in the dry needling group obtained a successful outcome at 3 months than in the MT plus exercise group At 3 months, the effect sizes were large in favor of the electrical dry needling group for all outcome measures. Incorporating electrical dry needling into an MT and exercise regimen was more successful than MT and exercise alone in relieving pain, function, and related-disability.
(Dunning, Butts, Young, et al., 2018)	RCT	North America/ USA	LBP	Dry Needling	ODI, PSFS, NPRS, and PPT	Results of this RCT indicated no between-group differences between patients experiencing NSLBP who received a semi-standardized NTM or a segmental and distal DN

						approach without needle manipulation.
(Vervullens et al., 2022)	RCT	Europe/ Belgium	Knee OA	Dry Needling	pain, central pain processing, muscle co-contraction and spatiotemporal parameters during gait in knee osteoarthritis patients.	When compared to fake needling, dry needling has no greater effect on pain, central pain processing, muscular co-contraction, or gait pattern 15 minutes and three days after intervention. The mean conditioned pain modulation scores were lower following sham needling than after dry needling. More research is still required.
(Pang et al., 2022)	RCT	North America/ USA	Knee OA	Ultrasound-guided dry needling and dry needling	VAS and KOOS subscales	US-guided DN with exercise therapy may be more effective than traditional DN with exercise therapy or exercise therapy alone in reduce pain of KOA.
(Sutlive et al., 2015)	RCT	North America/ USA	Patello femoral Pain Syndrome	Trigger Point Dry needling	AKPS and LEFS for Pain and Disability, Global Rating of Change (GROC) questionnaire	The authors believe that this was the first study to examine the effects of DN in a population of individuals with PFPS. Both the DN and SH groups experienced clinically meaningful reductions in pain during the study period.
(Jimenez-del-Barrio et al., 2022)	Systematic Review and Meta-Analysis	Europe/ Spain	Hip and Knee OA	Dry needling	Pain intensity	Very low-quality evidence suggests a positive effect of DN for reducing pain intensity and improving physical function in the short term in patients with osteoarthritis. Further investigation is needed to determine medium- and long-term effects.
(Bazzaz-Yamchi et al., 2021)	Pilot Study	Asia/Iran	LBP	Dry Needling	VAS, PKE, FFD test, and FRI	A single session of deep DN improved pain and function and increased hamstring flexibility. This pilot study supports the use of DN in patients with LBP and hamstring tightness; however, future research with a rigorous study design of randomized controlled trial is required to confirm the findings.

(Amani et al., 2022)	Preliminary Study	Asia/Iran	Knee OA	Dry Needling	Visual Analog Scale (VAS)	The application of one session DN can lead to improvement in pain intensity in participant with mild to moderate KOA
(Ceballos-Laita et al., 2019)	RCT	Europe/ Spain	Hip OA	Dry Needling	Pain intensity (visual analogic scale), passive hip ROM (universal goniometer and digital inclinometer) and physical function (30s chair-stand test and 20m walk test)	Pain, hip ROM, and physical function improved after the application of DN in active MTrPs of the hip muscles in patients with hip OA.
(Lara-Palomo et al., 2022)	RCT	Europe/ Spain	Chronic Low Back Pain	Electrical Dry Needling	RMDQ, ODI, VAS	Although physiotherapy with dry needling and electrical dry needling has proven positive effects on chronic low back pain. the results of studies into the duration of the analgesic effect and the dose required, for example, are contradictory . Therefore, further research is required to evaluate the specific components of the treatments administered by physical therapists.
(Schneider et al., 2022)	Quasi-Experimental Randomized Control Study	North America/ USA	Gluteus Medius	Trigger Point Dry Needling	HHD and sEMG	Application of TDN to latent trigger points within the gluteus medius can significantly increase gluteus muscle force production immediately following intervention while reducing the level of muscle activation required during contraction.
(Dunning, Butts, Henry, et al., 2018)	RCT	Europe/ Spain	Plantar Fascitis	Electrical Dry Needling	Numeric Pain Rating Scale, Lower Extremity Functional Scale (LEFS), Foot Functional Index (FFI),Global Rating of Change (GROC)	Patients with Plantar Fasciitis who got electrical dry needling in addition to manual treatment, exercise, and ultrasound improved considerably more than those who had manual therapy, exercise, and ultrasound alone.
(Sharif et al., 2022)	RCT	Asia/ Pakistan	Patellar Tendonitis	Ultrasound guided dry needling	VAS, VISA-P, KOOS	The results of the current study suggest, ultrasound guided DN of patellar tendon in combination with CPT reduced pain, improved function, and showed a tendency to decrease tendon thickness in patients with patellar tendinopathy.

(Rahou-El-Bachiri et al., 2020)	Systematic Review and Meta-Analysis	Europe/ Spain	Knee pain	Trigger Point Dry needling	Pain and pain- related disability	Low to moderate evidence suggests a positive effect of trigger point dry needling on pain and related disability in patellofemoral pain, but not knee osteoarthritis or post-surgery knee pain, at short-term. More high-quality trials investigating long-term effects are clearly needed.

Legend: PPT: Pressure Pain Threshold; VAS: Visual Analog Scale; NPRS: Numeric Pain Rating Scale; NDI: Neck Disability Index; KOOS: Knee Injury and Osteoarthritis Outcome Score; PKE: Passive Knee Extension; FFD: Finger-floor distance; WOMAC: Western Ontario and McMaster; DASH: Disability of the Arm, Shoulder, and Hand; SPADI: Shoulder Pain and Disability Index; ODI: Oswestry Disability Index: PSFS: Patient Specific Functional Scale; FHSQ: Foot Health Status Questionnaire.

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Conceptualization – J.A.M, Methodology – M.G.G and J.A.M , Acquisition, analysis, and interpretation of data – J.A.M, M.G.G, J.R.R, J.V.P, Writing, review, and editing – J.A.M and M.G.G. Research advising – E.D.P. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Data Availability

No data was used for the research described in the article.

List of Abbreviations

PPT: Pressure Pain Threshold;
VAS: Visual Analog Scale;
NPRS: Numeric Pain Rating Scale;
NDI: Neck Disability Index;
KOOS: Knee Injury and Osteoarthritis Outcome Score;
PKE: Passive Knee Extension;
FFD: Finger-floor distance;
WOMAC: Western Ontario and McMaster;
DASH: Disability of the Arm, Shoulder, and Hand;
SPADI: Shoulder Pain and Disability Index;
ODI: Oswestry Disability Index;
PSFS: Patient Specific Functional Scale;
FHSQ: Foot Health Status Questionnaire;

MT: manual therapy ;

ET: exercise therapy.

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The Burden of COVID-19 Vaccine Side Effects on Nursing Staff in Palestine

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ABSTRACT

This study investigates the impact of various COVID-19 vaccine side effects on nursing staff in Palestine. A quantitative cross-sectional study design was used, and 355 nurses participated by completing a self-administered questionnaire via Google Forms. These nurses worked in private and governmental hospitals and health centres in Palestine. The study showed that 55.2% of participants were hesitant to receive the vaccine. The majority of participants received the Pfizer vaccine (46.5%). Moreover, 50.7% reported experiencing post-vaccination side effects, with 37.5% describing them as mild. The most common side effects included fatigue (48.4%), pain at the injection site (46.2%), fever (46.2%), and headache (39.1%). The impact of different types of COVID-19 vaccines on missed work due to side effects was most notable after the first dose (21.7%), and the side effects were mainly mild and disappeared after one day (34.6%). Participants expressed concerns about safety, effectiveness, and short- and long-term side effects of vaccines.

Keywords: COVID-19, Immunity, Nursing, Hesitancy, Vaccines, Side effects.

1. Introduction

The COVID-19 pandemic originated in Wuhan, China, in December 2019 (Platto et al., 2020) and rapidly spread globally, causing widespread morbidity and mortality (Amer et al., 2024; Naqid et al., 2024; Orebi et al., 2022). The infection has resulted in more than two million deaths and over 107 million cases worldwide, including over 3,000 deaths and over 300,000 cases in Palestine (Shouli et al., 2022). As nurses play a crucial role in combating the pandemic, the number of COVID-19 cases among them was proportionately high (Maraqa et al., 2021; Naqid et al., 2024).

Vaccination offers a safer path to adaptive immunity than contracting the virus itself (Shouli et al., 2022). Although no vaccine is without potential side effects, COVID-19 vaccines utilise acquired artificial active immunity, relying on the adaptive immune response and immune memory. Their primary effect is reducing severe illness and death. However, vaccine effectiveness wanes over time and with the emergence of new variants (Barouch, 2022; Feikin et al., 2022.; Sette & Crotty, 2021). Despite the proven life-saving benefits of vaccines, some regions have experienced low acceptance rates (Eterafi et al., 2024). Nurses' attitudes toward vaccination, shaped by various factors such as their understanding of its importance, are critical, as they are considered a trusted source of information for others (Orebi et al., 2022).

There are different vaccine technologies in existence, including mRNA vaccines (Pfizer-BioNTech, Moderna), viral vector vaccines (Janssen, Sputnik, AstraZeneca), and inactivated vaccines (Sinopharm, Sinovac, COVAXIN) (Desai et al., 2023). Due to the rapid development of these vaccines, vaccine hesitancy has become a significant public health concern, driven by misinformation and rumours regarding vaccine safety and efficacy (Desai et al., 2023; Nwachukwu et al., 2024; Orebi et al., 2022). Factors influencing vaccine acceptance include awareness, perceived side effects, attitudes, perceived susceptibility, social influences, and trust in the medical community (Orebi et al., 2022). Rapid vaccine development, media attention, and anti-vaccination groups have also contributed to hesitancy. Misinformation concerning infertility and other severe side effects has also fuelled vaccine hesitancy among some nurses and the public (Desai et al., 2023). Transparency and accurate information are crucial for increasing vaccine confidence and addressing concerns about side effects (Amer et al., 2024). Common side effects are generally mild to moderate (fatigue, chills, fever, myalgia, headache, diarrhea, nausea, and injection site reactions) and manageable (Abukhalil et al., 2024; Ahmed Mohamed Ibrahim et al., 2024). Serious side effects, though rarer, have been reported (Abukhalil et al., 2024). Some studies show that women report side effects more than men (Sedaghat et al., 2024).

This research aims to assess the burden of COVID-19 vaccine side effects on Palestinian nurses, examining potential contributing factors, including age and gender. Due to the limited research on this topic in Palestine, the study aims to provide databased recommendations to enhance nurse support and minimize the impact of side effects on their work. Prior research has indicated vaccine hesitancy and fear of side effects among healthcare workers (Maraqa et al., 2021; Shouli et al., 2022). This study also investigates the relationship between vaccine hesitancy among nurses and the burden of COVID-19 vaccine side effects. Additionally, it aims to provide insights into future vaccination efforts in the event of a COVID-19 resurgence or the reuse of similar vaccine technologies in future epidemics.

2. Methods

A cross-sectional quantitative study was conducted using a convenience sampling method. The sample size was determined with a 95% confidence level and a 5% margin of error. The calculated sample size was 374, and the final response rate was around 95%, resulting in a final sample of 355 nurses. Data were collected using a structured, pretested questionnaire administered via Google Forms and distributed through visits and social media groups for nurses. The study included an appropriate sample of nurses from primary health care centres and governmental and non-governmental hospitals and centres in Palestine. The data were collected after obtaining approval from the Ethical Review Committee at Modern University College (Ref: muc006/2024), between October 15, 2024, and December 1, 2024. Approximately 13,000 nurses work in governmental and private hospitals, centres, and outpatient clinics in Palestine (West Bank), according to the Palestinian Nursing Syndicate.

Nurses from northern (Jenin, Tubas, Nablus, Qalqilya, Tulkarem), central (Jerusalem, Ramallah, Salfit, Jericho), and southern (Hebron, Bethlehem) cities were included. Participants were selected from various departments, including intensive care, emergency, neonatal, gynaecology, and surgery.

The survey was adjusted and adapted from previous research to test nurses' experiences with the vaccination process and to collect data on related side effects (Ahmed Mohamed Ibrahim et al., 2024; Al-Hatamleh et al., 2022; Chrissian et al., 2022; Dejen Tilahun et al., 2024; Elhadi et al., 2021; Maraqa et al., 2021; Naqid et al., 2024; Shouli et al., 2022; Zare et al., 2022).

The questionnaire consists of four sections: Demographic data: (age, gender, marital status, profession, place of work, years of experience). General knowledge: includes chronic medical problems, a healthy lifestyle, and the annual flu vaccination before the COVID-19 vaccine. COVID-19 information: about the type of vaccine and the number of doses, about vaccine hesitancy and refusal, about infection with this virus after vaccination, and admission to hospital after vaccination. Side effects of vaccines, including serious complications of the vaccine, the severity of side effects after vaccination, the nature of symptoms, the time required for vaccination symptoms to disappear, if there is a need to miss work after receiving the doses, concerns about the safety and effectiveness of the vaccine, and concerns about short- and long-term side effects.

Some of the questionnaire's items were improved after it was piloted with 40 respondents to assess its comprehensibility, face validity, and expected time to complete. Certain things were eliminated and merged with other subjects in response to the feedback received. To avoid possible bias. The reliability was indicated by the trend data's determined Cronbach's alpha of 79%.

2. 1. Data Analysis

The collected data were analysed by the Statistical Package for Social Sciences (SPSS), Version 27. Data entry was performed and double-checked for outliers or errors. Both descriptive and inferential statistical analyses were conducted. Descriptive statistics, including frequencies, percentages, mean scores, and Standard Deviation (SD), were used to describe the study variables. Regarding inferential statistics, an independent t-test and a One-Way ANOVA, and a chi-square test were conducted to assess the differences between variables.

3. Results

3. 1. Demographic Variables

The study included 355 participants. Most were female (62.0%), compared to males (38.0%). The majority were aged 20–29 years (67.3%), followed by those aged 30–39 years (13.5%), 40–49 years (15.5%), and those aged 50 years or older (3.7%). Regarding marital status, 52.1% were married, 46.8% were single, and 1.1% were divorced. In terms of education, 66.5% held a Bachelor's degree, 19.7% had a diploma, and 13.8% pursued higher education (Master's or PhD). Participants were almost evenly distributed between governmental (48.7%) and private (51.3%) sectors. Regionally, 43.1% worked in the central region (Jerusalem, Ramallah, Salfit, Jericho), 38.9% in the southern region (Hebron, Bethlehem), and 18.0% in the northern region (Jenin, Tubas, Nablus, Qalqilya, Tulkarem). Most participants had 1–5 years of experience (60.8%), while 11.5% had 6–10 years, and 27.6% had more than 10 years of experience.

Table 1. Demographic Variables of the Participants (n=355)

Demographic variables		n	%
Gender	Male	135	38.0%
	Female	220	62.0%
Age group	20-29 years old	239	67.3%
	30-39 years old	48	13.5%
	40-49 years old	55	15.5%
	>49 years old	13	3.7%
Marital status	Single	166	46.8%

	Married	185	52.1%
	Divorced	4	1.1%
Level of education	Diploma Degree	70	19.7%
	Bachelor's Degree	236	66.5%
	Higher Education (Master's or PhD)	49	13.8%
Working sector	Governmental	173	48.7%
	Private	182	51.3%
Working region	North (Jenin, Tubas, Nablus, Qalqilya, Tulkarem)	64	18.0%
	Middle (Jerusalem, Ramallah, Salfit, Jericho)	153	43.1%
	South (Hebron, Bethlehem)	138	38.9%
Experience	1-5 years	216	60.8%
	6-10 years	41	11.5%
	>10 years	98	27.6%

3. 2. Assessing Health Practices, COVID-19 Vaccination Attitudes, and Post-Vaccination Experience

The assessment of health practices, COVID-19 vaccination attitudes, and post-vaccination experiences revealed that 58.0% maintained a healthy lifestyle, while 42.3% reported receiving annual flu vaccinations prior to the COVID-19 pandemic. A majority (79.4%) did not have chronic medical problems. The primary source of COVID-19 information was the WHO (50.4%), followed by multiple sources (28.2%). Vaccine hesitancy was observed in 55.2% of participants, and 42.5% had previously refused the COVID-19 vaccine. About 52.1% encouraged others to get vaccinated. Regarding vaccine types, 46.5% received the Pfizer/BioNTech vaccine, followed by Sputnik (19.7%) and Moderna (17.7%). Most participants (47.0%) received two doses, and 35.2% were willing to receive a booster if recommended. Post-vaccination, 36.6% reported contracting COVID-19, and 13.5% required hospitalisation. 41.1% reported feeling safer post-vaccination, while 32.1% did not feel safer, and 26.8% were uncertain.

3. 3. Side Effects of Vaccines

The analysis of vaccine side effects revealed that 55.5% expressed concern about serious complications, while 50.7% reported experiencing side effects post-vaccination. Regarding the severity of symptoms, 37.5% described them as mild, 31.0% as moderate, and 7.6% as severe, while 23.9% reported no symptoms. The most common side effects included fatigue (48.4%), pain at the injection site (46.2%), fever (46.2%), and headache (39.1%). Injection site reactions involved pain (54.9%), redness (7.6%), and swelling (8.5%). Side effects were most commonly reported after the first dose (32.7%), followed by the second dose (14.1%) and the third dose (4.2%), while 20.3% experienced side effects after each dose. Symptoms resolved after one day in 34.6% of cases, within 48 hours in 22.0%, and within 72 hours in 11.8%. Missing work due to side effects was reported by 21.7% after the first dose, 14.1% after the second, and 10.4% after all doses, while 47.9% did not need to miss work.

3. 4. Concerns Regarding COVID-19 Vaccines

The analysis of concerns regarding COVID-19 vaccines shows that participants generally exhibited "good concern" across all assessed aspects, with a total mean score of 3.13 (SD = 0.918). Specifically, concerns about vaccine safety had a mean score of 3.08 (SD = 1.142), effectiveness scored 3.14 (SD = 1.146), short-term side effects scored 3.10 (SD = 1.082), and long-term side effects scored 3.18 (SD = 1.190). Based on the cutoff point (<3 indicating "bad concern" and ≥3 indicating "good concern"), all items reflected a good level of concern.

Table 2. Concerns Regarding COVID-19 Vaccines

Item	Mean	SD	%	Status
1. I have concerns about the COVID-19 vaccine's safety	3.08	1.142	61.6%	Good Concern
2. I have concerns about the COVID-19 vaccine's effectiveness	3.14	1.146	62.8%	Good Concern
3. I have concerns about the short-term side effects	3.10	1.082	62%	Good Concern
4. I have concerns about the long-term side effects	3.18	1.190	63.6%	Good Concern
Total Mean Score (4 items)	**3.13**	**.918**	**62.6%**	**Good Concern**

Cutt of point: <3 bad concern, ≥3 good concern

3. 5. Factors Associated with the Severity of COVID-19 Side Effects

As shown in **Table 3**, participants in the study were hesitant about vaccination, and those who previously refused vaccines reported more severe side effects. Those who did not advise others to be vaccinated also experienced more severe side effects. Participants receiving the Pfizer/BioNTech vaccine reported more severe side effects compared to those receiving the AstraZeneca/Oxford vaccine. Unwillingness to receive a booster dose was associated with higher side effect severity, as was contracting COVID-19 after vaccination. Conversely, those who felt safer dealing with COVID-19 patients after vaccination reported less severe side effects.

Table 3. Factors Associated with the Severity of COVID-19 Side Effects (n=355)

Factors		*N*	*Mean*	*SD*	*P-value*
Do you have COVID–19 vaccine hesitancy?	*Yes*	*196*	*2.37*	*0.91*	*.003**
	No	*103*	*2.05*	*0.81*	
	Maybe	*56*	*2.04*	*0.93*	
Did you refuse to receive COVID-19 vaccine in the past?	*Yes*	*151*	*2.39*	*0.91*	*.002**
	No	*204*	*2.10*	*0.87*	
Did you advise other people to get vaccinated for COVID–19?	*Yes*	*185*	*2.13*	*0.86*	*.043**
	No	*170*	*2.32*	*0.93*	
What is the type of vaccine you received?	*Moderna*	*63*	*2.19*	*0.80*	*.043**
	Sputnik	*70*	*2.19*	*0.89*	
	Sinopharm	*20*	*2.15*	*1.14*	
	Pfizer/BioNTech	*165*	*2.33*	*0.88*	
	AstraZeneca/Oxford	*30*	*1.77*	*0.82*	
	J&J/Janssen	*7*	*2.57*	*1.27*	
Are you willing to receive a booster dose if recommended by health authorities?	*Yes*	*125*	*2.10*	*0.91*	*.009**
	No	*154*	*2.39*	*0.89*	
	Maybe	*76*	*2.08*	*0.84*	
Did you get infected with COVID-19 after vaccination?	*Yes*	*130*	*2.51*	*0.86*	*<.001**
	No	*186*	*2.03*	*0.88*	
	Maybe	*39*	*2.18*	*0.88*	
Do you think getting vaccinated made you feel safer while dealing with Corona patients?	*Yes*	*146*	*2.08*	*0.86*	*.035**
	No	*114*	*2.33*	*0.87*	
	Maybe	*95*	*2.32*	*0.97*	

A higher mean score means higher severity of side effects (Min=1, Max=4)
*Independent t-test and One-Way ANOVA; *Significant at p=<0.05*

3. 6. Associated Factors that Affect COVID-19 Vaccine Hesitancy

COVID-19 vaccine hesitancy was significantly associated with the working sector. Participants working in the governmental sector were more likely to report vaccine hesitancy (56.6%) compared to those in the private sector (43.4%), while individuals without hesitancy were more prevalent in the private sector (65.0%) compared to the governmental sector (35.0%). Those who were uncertain ("Maybe") were more evenly distributed but leaned slightly toward the private sector (53.6%). The association was statistically significant ($X^2 = 12.8$, $p = .002$). Years of experience showed a statistically significant relationship with vaccine hesitancy ($X^2 = 13.6$, $p = .009$). The majority of hesitant individuals had 1-5 years of experience (61.7%), followed by those with >10 years (30.6%), while the 6-10 years group had the lowest proportion (7.7%). A similar trend was observed among non-hesitant individuals, where the 1-5 years group also dominated (64.1%), followed by 6-10 years (18.4%) and >10 years groups (17.5%). Among those who were uncertain ("Maybe"), most had 1-5 years of experience (51.8%), followed by >10 years (35.7%), with the 6-10 years group again being the least represented (12.5%). Although a significant association was found, the predominance of the 1-5 years group across all categories suggests that other factors may also contribute to vaccine hesitancy.
Post-vaccination side effects were strongly associated with hesitancy. Among those with hesitancy, 61.7% reported experiencing side effects, compared to 37.9% in the "No" group and 35.7% in the "Maybe" group. Those without hesitancy were more likely to report no side effects (54.4%), compared to 26.0% in the hesitant group and 37.5% in the "Maybe" group. The "Maybe" group had the highest proportion of individuals uncertain about side effects (26.8%), compared to 12.2% in the hesitant group and 7.8% in the "No" group. The association was highly significant ($X^2 = 35.8$, $p = .001$).

Table 4. Associated Factors that Affect COVID-19 Vaccine Hesitancy (n=355)

		Do you have COVID–19 vaccine hesitancy?						***X^2***	***P-value***
		Yes		***No***		***Maybe***			
		n	***%***	***n***	***%***	***n***	***%***		
Working sector	*Governmental*	*111*	*56.6%*	*36*	*35.0%*	*26*	*46.4%*	*12.8*	*.002**
	Private	*85*	*43.4%*	*67*	*65.0%*	*30*	*53.6%*		
Experience	*1-5 years*	*121*	*61.7%*	*66*	*64.1%*	*29*	*51.8%*	*13.6*	*.009**
	6-10 years	*15*	*7.7%*	*19*	*18.4%*	*7*	*12.5%*		
	>10 years	*60*	*30.6%*	*18*	*17.5%*	*20*	*35.7%*		
Have you suffered from any side effects post-vaccination?	*Yes*	*121*	*61.7%*	*39*	*37.9%*	*20*	*35.7%*	*35.8*	*.001**
	No	*51*	*26.0%*	*56*	*54.4%*	*21*	*37.5%*		
	Maybe	*24*	*12.2%*	*8*	*7.8%*	*15*	*26.8%*		

*Chi-square test;*Significant at p=<0.05*

3. 7. Association Between the Need to Miss Work After Which Dose and Type of Vaccine

Table 5 shows that Pfizer/BioNTech recipients were the most likely to report missing work, particularly after the second dose (62%), although 50% of Pfizer recipients reported no missed work. Moderna recipients most commonly missed work after the first dose (29.9%). Sputnik recipients frequently missed work after all doses (27%). Sinopharm recipients missed work most often after the first dose (5.2%) and third dose (14.3%), but a high proportion (4.7%) reported no missed work. AstraZeneca/Oxford recipients reported the lowest need to miss work, with only 12.4% missing any work. J&J/Janssen recipients also largely didn't miss work, with only small percentages missing work after the second dose (4%) or all doses (2.7%). The study concludes that vaccine type influences missed work, with Pfizer/BioNTech having the highest impact, especially after the second dose.

Table 5. Association Between Needed to Miss Work after which Dose and Type of Vaccine (n=355)

Variable		Needed to miss work after which dose?										X^2	P-value
		1st dose		2nd dose		3rd dose		All doses		No need			
		n	%	n	%	n	%	n	%	N	%		
What is the type of vaccine you received?	Moderna	23	29.9%	5	10.0%	3	14.3%	8	21.6%	24	14.1%	32.7	.036*
	Sputnik	18	23.4%	8	16.0%	6	28.6%	10	27.0%	28	16.5%		
	Sinopharm	4	5.2%	3	6.0%	3	14.3%	2	5.4%	8	4.7%		
	Pfizer/BioNTech	28	36.4%	31	62.0%	7	33.3%	14	37.8%	85	50.0%		
	AstraZeneca/Oxford	4	5.2%	1	2.0%	2	9.5%	2	5.4%	21	12.4%		
	J&J/Janssen	0	0.0%	2	4.0%	0	0.0%	1	2.7%	4	2.4%		

Chi-square test
**Significant at p=<0.05*

4. Discussion

The burden of COVID-19 vaccines among nurses in Palestine was measured, focusing on two aspects: vaccine hesitancy and the incidence and severity of post-vaccination side effects. The results presented above shed light on the complex interplay of factors contributing to this burden. Our findings demonstrate a clear link between vaccine hesitancy and the perception of side effect severity, suggesting that concerns about adverse reactions may play a significant role in vaccine uptake. Furthermore, the observed differences in side effect profiles across vaccine types, along with the association between specific vaccines and time off work, underscore the practical impact of vaccination on healthcare personnel. The significant link between hesitancy and reported side effect severity among participants can be explained by the fact that individuals who were hesitant, had previously refused vaccination, or did not advise others to get vaccinated reported more severe side effects. This aligns with the idea that individuals with less knowledge or reliable information about vaccines may experience more fear and perceived side effects. Other studies have shown varying levels of vaccine acceptance, with one finding 63% of Palestinians willing to be vaccinated, particularly women, married individuals, and those with more knowledge about the vaccine (Maraqa et al., 2021; Zawahrah et al., 2021). Another study highlighted the role of misinformation and mistrust in vaccine hesitancy (Alalawi et al., 2024; Al-Hatamleh et al., 2022; Biswas et al., 2021). Regarding side effects, fatigue, fever, injection site pain, and headache were the most commonly reported symptoms on the first day of vaccination, with most resolving the same day. The varying percentages of reported side effects across doses may be attributed to participants perceiving them as a normal physiological response. This contrasts with a study on Birzeit University staff, where approximately one-third of participants reported no adverse effects after any dose of the Pfizer-BioNTech vaccine. The most commonly reported side effects in that study were fever, chills, headache, fatigue, pain at the injection site, muscle pain, joint pain, and some allergic reactions (Abukhalil et al., 2024). Other studies have also reported similar common side effects, with varying frequencies (Alhazmi et al., 2021; Colleran et al., 2024; Zare et al., 2022). Our study found greater vaccine hesitancy among nurses in governmental hospitals compared to those in private hospitals, potentially due to rumours, lower confidence in vaccine quality, and a lack of awareness campaigns. This finding is partially supported by some studies suggesting that vaccine acceptance varies by work sector (Alhazmi et al., 2021; Eterafi et al., 2024; Park & Ahn, 2023), although others found no such influence. We also found that less experienced nurses were more hesitant, which is consistent with other studies (Mohammed et al., 2021; Odejinmi et al., 2022). Post-vaccination side effects were strongly associated with hesitancy, aligning with other research highlighting concerns about short-term and long-term side effects as major drivers of hesitancy (Ahmed Mohamed Ibrahim et al., 2024; Azimi-nezhad et al., 2022; Odejinmi et al., 2022; Perrone et al., 2023). Nurses who didn't experience side effects were less hesitant, supporting the idea that the severity of side effects correlates with vaccine hesitancy (Aloweidi et al., 2021; Desai et al., 2023; Hoffman et al., 2022). Finally, our study showed a

significant association between missing work and the type of vaccine, with Pfizer/BioNTech recipients more likely to miss work, particularly after the second dose. While some studies have reported similar findings regarding Pfizer side effects and missed work (Abukhalil et al., 2024), others have not found a significant correlation between vaccine type and missed work due to side effects (Alguraini et al., 2024; Al-Matouq et al., 2022). AstraZeneca/Oxford recipients in our study were least likely to miss work, which aligns with some studies showing milder side effects (Darraj & Al-Mekhlafi, 2022; Eterafi et al., 2024). J&J/Janssen recipients in our study also reported low rates of missed work, which is consistent with other findings (Okpani et al., 2023).

5. Conclusion

A significant association was found between vaccine hesitancy and the perceived severity of side effects. Additionally, a correlation was observed between the number of doses received and the incidence of reported side effects. Nurses in governmental hospitals and less experienced nurses showed higher vaccine hesitancy than others. The study strongly reinforces the link between post-vaccination side effects and hesitancy. Receiving the Pfizer/BioNTech vaccine, especially the second dose, was associated with a higher likelihood of missing work due to side effects. This study is not without limitations. First, the reliance on self-reported questionnaires introduces the potential for recall bias, particularly given that the data collection occurred several years after the initial vaccination campaigns. Participants' memories of side effects may be incomplete or influenced by other factors. Second, the study's data collection period coincided with a time of restricted access to health facilities due to political circumstances and military barriers, which likely impacted the response rate and may have introduced selection bias. Finally, the study's focus on nurses working in Palestine limits the generalisability of the findings to other healthcare providers or populations in different settings. Further investigation into the long-term effectiveness of different COVID-19 vaccine types is warranted. Measuring antibody titres in vaccinated nurses could provide valuable data on vaccine efficacy over time and inform decisions regarding the need for and timing of booster doses. Additionally, research exploring vaccine hesitancy and side effects among other healthcare provider groups, both within Palestine and in other countries, would broaden our understanding of the challenges and inform targeted interventions to improve vaccine confidence and uptake.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request. The datasets generated and analysed during the current study are not publicly available due to privacy and ethical restrictions but are available from the corresponding author on reasonable request. For further enquiries or access to the data, please contact:

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Conflicts of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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A Survey on the Influence of Blockchain and Neural Network Technologies on Smart Grid Systems

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ABSTRACT

Energy transactions benefit from blockchain technology because it creates an independent system that provides secure data protocols and protects against unauthorised alterations of information while strengthening protection. Multipurpose blockchain tools let traders conduct secure peer-to-peer energy exchanges, and they can run automated networks while diminishing dependence on central control systems. Small and distributed energy control methods decrease infrastructure vulnerability by shielding it from cyber threats while creating a tamperproof network, which builds modern energy security and visibility. Organisations use advanced machine learning algorithms to study historical and real-time data to optimise energy distribution, identify consumption patterns, and detect anomalies. The predictive models enable better decision-making through preventive maintenance plans, reduced energy losses, and optimised distribution of electricity loads in the grid system. The research investigates detailed implementations of predictive models that unite neural networks and blockchain technology into a system that builds up smart grid functions. These technologies form a synergistic relationship that enables smart automation systems along with continuous real-time monitoring and boosted operational efficiency. The study investigates actual blockchain-based energy market examples alongside case studies on predictive maintenance carried out through AI and decentralised power trading platforms. The research results show that integrating blockchain with neural networks can enhance smart grid security and reliability while also supporting the development of a sustainable and adaptable energy system. Through their resolution of scalability problems and regulatory requirements as well as computational limits, these technologies establish future frameworks for smart power networks of the next generation. The survey findings create a basis for researchers to use for advancing energy informatics and smart grid innovation in the future.

Keywords: Blockchain; Neural Network Technologies; Smart Grids; Security and Reliability; Applications of Blockchain and Neural Network Technologies.

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1. Introduction

Smart grids emerge as an upgraded energy system through the combination of smart communication systems, automatic systems, data analytical mechanisms to optimize power source management, distribution networks and consumption operations (Khan & et al, 2023). Smart grids transform traditional power grids by implementing bidirectional communication, real-time monitoring systems, and adaptive control mechanisms to enhance operational efficiency and system resilience (Gonen, 2014). Javaid et al. (2018) and Li et al. (2023) explain that smart grids improve energy reliability, support renewable energy connections, and manage power demands—thereby lowering the costs of operations and minimizing environmental effects (Li & et al, 2023). The rising adoption of solar and wind energy enables smart grids to carry out essential tasks such as balancing power supply and demand, preventing grid instabilities, and promoting ecological stability. Advanced computational security solutions must develop for decentralized energy platforms to ensure the secure and efficient management of vast amounts of data and transaction flows (Javaid & et al, 2018).

Smarter energy grids face several significant challenges, including critical security threats to their systems, faulty marketplace trading systems, and complex predictive servicing requirements. Leading-edge technologies, which include neural networks and blockchain solutions, need to be implemented, as they will boost security parameters, decision-making capabilities, and overall operational efficiency (Hua & et al, 2022).

Blockchains represent an independent ledger technology that secures energy deals by being tamper-proof, making details transparent, and stopping cyber theft attacks. The research by Wu et al. (2018) demonstrates that blockchain Peer-to-Peer (P2P) trading enables secure, direct transactions between energy producers and consumers by creating trust and reducing fees (Wu & et al, Towards collective energy Community: Potential roles of microgrid and blockchain to go beyond P2P energy trading, 2022).

Artificial Intelligence (AI) enables neural networks to provide predictive analytics, detect failures, and forecast energy demand, as they are a subset of AI. The work of Almasoudi et al. (2023) demonstrates how deep learning algorithms enhance live power forecasting, alongside improved electric grid reliability and enhanced power grid energy transmission performance. Traditional and current data analysis using neural networks helps forecast power outages and required maintenance, while simultaneously improving system reliability (Almasoudi, 2023).

Figure 1 relates the linkages between blockchain and other applications (Prakash & et al, 2022). The fusion of neural network technology with blockchain presents a powerful approach to enhancing the operation of smart grids. Blockchain ensures the secure and decentralized exchange of information, while neural networks facilitate real-time decisions with enhanced intelligence, making the grid more responsive and efficient.

The purpose of the study is to investigate the relationship that exists between blockchain and neural networks and their influence on smart grids with regard to energy management optimization, boosting cyber security measures, and enabling predictive maintenance. In simpler terms, the main goals of the research are:

- To understand the role played by blockchain in the security and transparency of smart grid transactions.
- To assess the capability of neural networks in predicting energy demand and identifying faults within the system.
- To assess the synergy of blockchain and neural networks on the smart grid technology performance.
- To find applicable examples of incorporating such technologies into energy systems.

This research is significant due to the anticipated outcome of building a more sustainable, secure, and intelligent energy infrastructure. Smart grids using blockchain technology and neural networks can attain greater efficiency and resilience, which would accelerate the adoption of decentralized renewable energy sources.

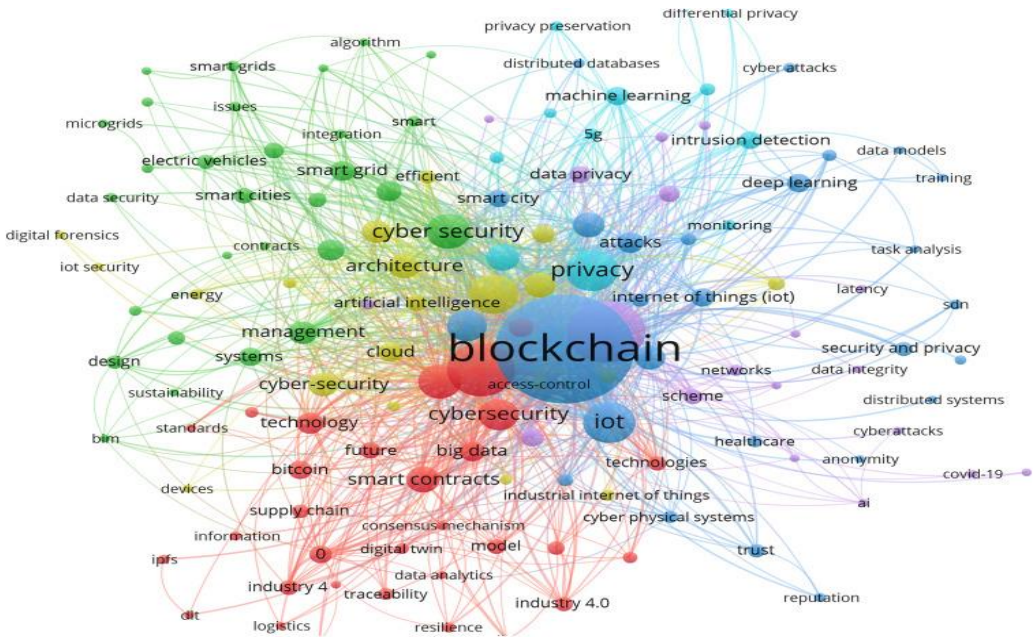

Figure 1. The correlation between Blockchain and different sections (Prakash et al, 2022) and (Marimi, 2025).

2. Fundamentals of Smart Grids

Smart grids comprise various components and subcomponents that integrate to enhance the efficiency, resiliency, and sustainability of today's energy systems. Alotaibi et. Al (2020) states that the primary components of smart circuits include (Alotaibi & et al, 2020):

- Energy is consumed optimally and in real time by monitoring and controlling its consumption in a way that reduces waste. Furthermore, controlled energy consumption is non-harmful.
- Utility to end-user and end-user to utility multi-channel communication that improves demand forecasting and nominal tariff rate execution for additional units sold service.
- Processes of the grid are observed and managed to guarantee stability on the grid as well as to eliminate failures.
- Alternative energy sources (solar panels, wind rotors) and energy storage systems, together with mobile devices that contribute to the grid decentralization, are included.
- Renewable energy technologies, especially solar photovoltaics, figure prominently in the economies of South Asian countries and correlate with increasing energy storage and facilitating flexibility of the grid, as stressed by Islam et al, 2024 (Islam & et al, 2024).
- Cyber protection of the grid devices in order to keep data traffic and transactions safe and systems operationally intact was and is to be enhanced.

By putting all these components into place, smart grids enable the reallocation of energy resources, optimize reliability, and facilitate the world's achievement of sustainable energy. While smart grids heavily rely on digital communications and information, Waseem and others (2023) argue that blockchain technology can be instrumental in securing smart grid (SG) transactions (Waseem & et al, Incorporation of blockchain technology for different smart grid applications: Architecture, prospects, and challenges, 2023). However, major obstacles hinder widespread adoption (see **Table 1**). The advanced computational requirements and delays associated with real-time computation may make it impossible to achieve SG applications in real time. Consequently, there must be frameworks that are designed in a way to blend both security and efficiency.

Table 1. Cybersecurity Threats to Smart Grids Based on the CIA Triad (Confidentiality, Integrity, and Availability according to (Waseem & et al, Incorporation of blockchain technology for different smart grid applications: Architecture, prospects, and challenges, 2023).

CIA	Attack
Confidentiality	Social Engineering, Eavesdropping, Traffic Analysis, Unauthorised Access, Password Pilfering, MITM, Sniffing, Replay, Masquerading, and Data Injection
Integrity	Tampering, Replay, Wormhole, False Data Injection, Spoofing, Data Modification, Time Synchronization, Load Drop, MITM, and Masquerading
Availability	Wormhole, Jamming, Denial of Service (DoS), LDoS, Buffer Overflow, Teardrop, Smurf, MITM, Spoofing, Puppet, Time Synchronization, and Masquerading

Moreover, to facilitate interoperability and reduce cybersecurity risks, standardized regulations are crucial, making blockchain an essential yet still evolving technology for the future evolution of SG. Khalid et al. (2024) argued that the shifts in energy supply and demand, the incorporation of renewable resources, and the limitation of turbine capacity present significant challenges. The research suggests that the transition to SG is crucial for the automation and digitalization necessary to integrate new renewable resources and promote sustainability. However, operational flexibility, regulatory compliance, and user participation remain emerging challenges for efficient execution of the implementation strategies. Critical issues, such as planning, security, and the integration of various systems, also require attention, which necessitates standard rules and contingency plans (Khalid, 2024). Smart grids collect data from multiple sources, including sensors, meters, and control systems. Treated effectively, such data could aid real-time decision-making. There is a need for prompt data storage, processing, and analysis. Conventional cloud-based mechanisms can lead to security and latency challenges, which creates a need for a shift to a decentralized solution such as blockchain and federated learning, as explored by Ahmed et al. (2022) (Ahmed & et al, 2022).

3. Blockchain Technology in Smart Grids

The decentralized ledger system of blockchain maintains a distributed network of several nodes, which ensures that data remains tamper-resistant and transparent while securing all transactions. Each transaction undergoes encryption and timestamping before being connected to other transactions, so that any alteration requires a network-wide consensus to be successful. According to Musleh (2019), various blockchains can be utilized for data protection across different smart grid tiers. Figure 2 illustrates that a distinct blockchain aggregator is responsible for each smart grid tier. The study concluded that by offering a dependable and secure platform for data storage, these blockchains should secure the smart grid. Furthermore, the identification of the particular consumer or producer is not directly connected to their identity within the blockchain environment. As a result, it will make the power system more resilient and less susceptible to hostile attacks (Musleh & et al, 2019).

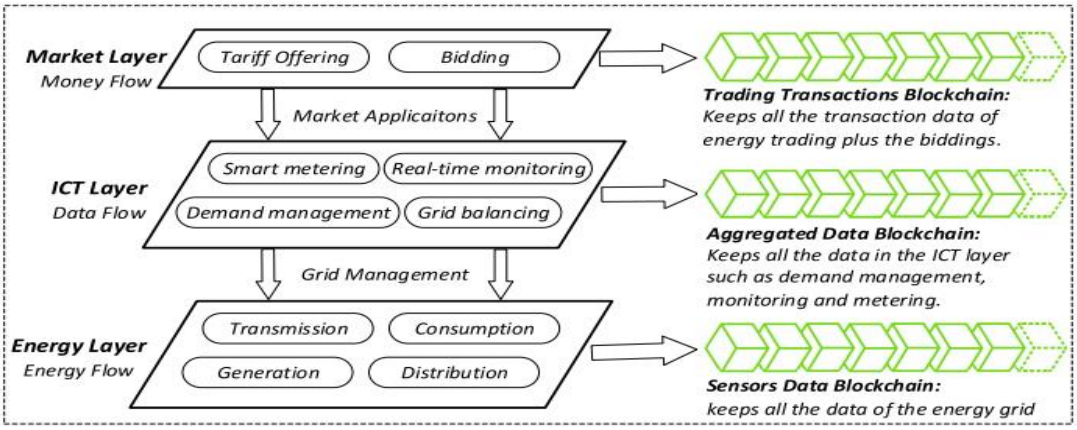

Figure 2. The Blockchain applications framework in smart grid security and data protection

According to Waseem et al. (2023), blockchain implements cryptographic principles with Proof of Work (PoW) and Proof of Stake (PoS) consensus mechanisms to achieve security controls as well as protected access in smart grid (SG) environments (Waseem & et al, 2023). Blockchain enables peer-to-peer (P2P) energy trading, through which prosumers, who engage in both production and consumption, can exchange their excess energy without the need for utility provider intermediaries. Wu et al. (2022) demonstrated that P2P energy trading facilitated through blockchain technology enhances decentralized power systems and promotes the adoption of renewable energy sources, alongside improved electricity delivery. The research outcomes confirmed that decentralized energy management benefits from a six-layered blockchain architecture because it delivers safe, automated transactions that perform efficiently. Anjimoon (2024) discovered that every measured metric of the AI-enhanced system had significantly improved. He stated that the decline in SAIFI and SAIDI demonstrated a notable increase in system reliability. While the rise in prediction accuracy validated the efficacy of AI in demand and supply forecasting, this also showed a drop in transmission and distribution losses and an increase in operational efficiency as presented in Figure 3 (Anjimoon & et al, 2024).

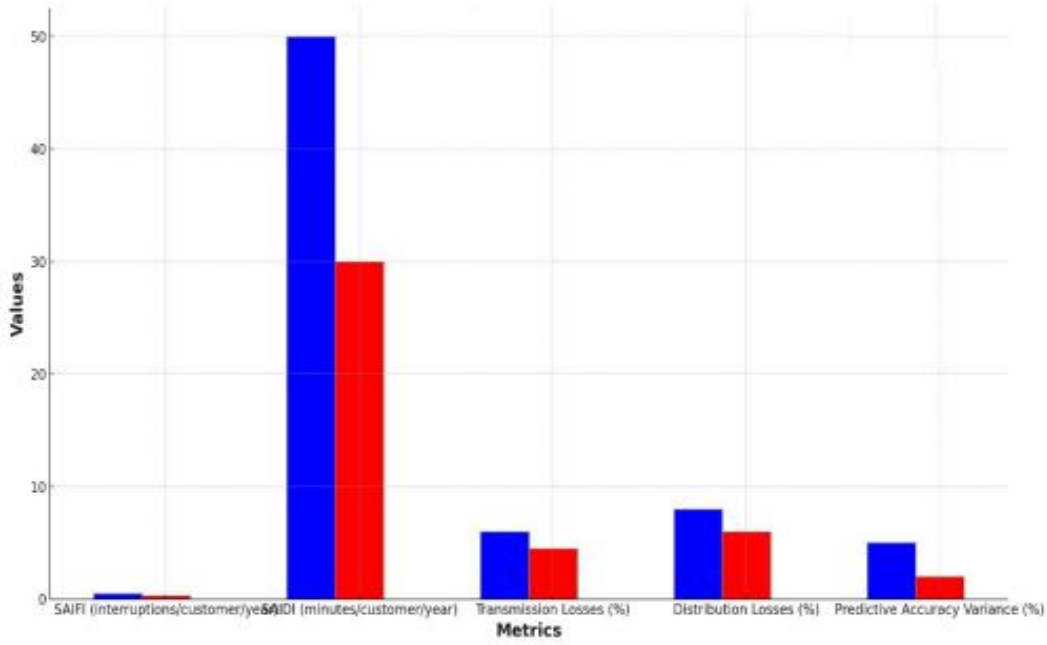

Figure3. Comparative Analysis of Grid Performance Metrics

The system establishes three levels of energy management: between households for individual use, within communities for internal exchange, and between communities for external energy transactions. The energy transaction method supports large-scale energy exchanges, combining resilience and security as it extends to the transportation, building, and industrial sectors (Figure 4) (Wu & et al, 2022).

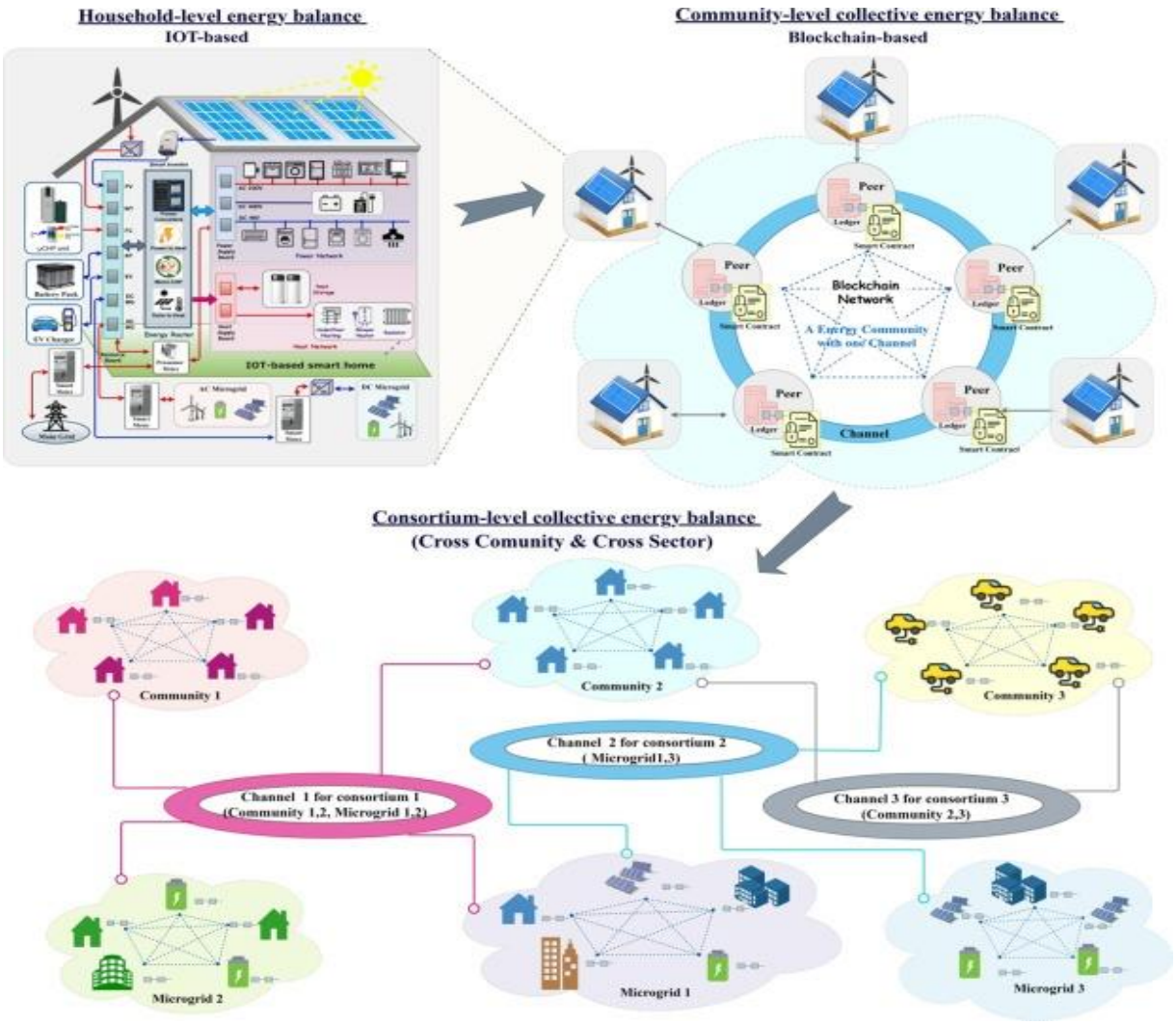

Figure 4. The hierarchical architecture based on Blockchain for a framework for cross-border energy networking

Smart grids benefit from enhanced security and transparent data management when utilizing blockchain, as it establishes a decentralized system that is free from single points of vulnerability and protects data from tampering. Research by Ferdous et al. (2023) has demonstrated that smart grids powered by blockchain technology decrease the exposure to cyberattacks which involve unauthorised access as well as data breaches and fraudulent energy results (Ferdous & et al, 2023).

Large-scale smart grid applications cannot function with traditional blockchain models and their Power of Work implementation because these systems require unrestrained computational power. According to Treiblmaier (2023), the Bitcoin network operates its Proof of Work consensus mechanism at an energy consumption level equivalent to small nation states, which justifies the implementation of PoS or Delegated Proof of Stake (DPoS) to achieve energy savings (Treiblmaier, 2023).

The transaction speed restrictions and throughput limitations faced by blockchain networks make it challenging for them to handle the rapidly increasing transactions that are crucial to smart grid operations. Hafid et al. (2020) demonstrate in their studies that Layer-2 solutions, including off-chain transactions and network partitioning, should boost blockchain scalability (Hafid & et al, 2020).

Appearing as a disruptive energy-market mechanism, blockchain enhances energy transaction security and raises transparency as well as accelerates operational efficiency. Its applications in P2P energy trading, smart contracts, and decentralized data management offer promising benefits for the future energy landscape. The adoption of blockchain technology faces three main barriers: high power consumption requirements, scalability, and regulatory compliance framework issues.

Future investigations in blockchain technology need to optimize framework implementations with energy-conscious consensus components and develop standardized policy frameworks to advance smart grid development.

Table 2. Comparison between Related Works in AI and Blockchain for Smart Grids**.**

Reference	Main Results	Research Gap
Ferdous et al. (2023)	Utilisation of Self-Sovereign Identity (SSI) and Distributed Ledger Technology (DLT) for enhancing the reliability of Renewable Energy Certificates (RECs), ensuring transparency and security in tracking renewable energy sources.	Lack of large-scale real-world implementations and interoperability challenges between different energy markets.
Hafid et al. (2020)	Addressed blockchain scalability issues through sharding, sidechains, and layer-2 solutions, improving the efficiency of smart grid applications.	Need for integration of AI-driven optimisation to further enhance blockchain performance and reduce energy consumption.
Prakash et al. (2022)	Investigated the role of blockchain in cybersecurity, protecting smart grids from data tampering, MITM attacks, DoS attacks, and unauthorised access.	Limited focus on AI-enhanced security mechanisms to predict and mitigate cyber threats proactively.
Treiblmaier (2023)	Analysed blockchain energy consumption and economic implications, highlighting challenges posed by high computational costs and environmental concerns.	Need for energy-efficient consensus mechanisms (e.g., Proof of Stake, Federated Learning) to make blockchain viable for smart grids.
Waseem et al. (2023)	Reviewed blockchain architectures, applications, and challenges in smart grids, with a focus on peer-to-peer (P2P) energy trading and decentralised energy markets.	Lack of AI-powered predictive models to enhance the efficiency of blockchain-enabled smart grids.
Wu et al. (2022)	Explored blockchain-based microgrid energy communities, facilitating decentralised energy transactions beyond traditional P2P trading.	Need for machine learning-based optimisation techniques to enhance energy dispatch and load balancing in blockchain-enabled smart grids.

The majority of research investigates blockchain characteristics or AI features independently, yet fails to establish a single framework that connects AI with blockchain for smart grids. The primary impediment to adoption consists of substantial power consumption; therefore, new methods to enhance smart grid consensus mechanisms must be developed. The implementation of blockchain technology at a large scale is minimal, while achieving energy market interoperability remains an essential technical challenge.

4. ANN Technology in Smart Grids

Artificial Neural Networks (ANNs) enhance the intelligence and efficiency of smart grids by improving energy forecasting, defect detection, and optimal power distribution. They are well-suited to handling complex and non-linear energy patterns, enabling renewable energy integration, load forecasting, and voltage stability analysis. Several studies have demonstrated that ANN-based models surpass statistical models in both short-term and long-term load forecasting. Almalaq et al. (2017) confirmed that ANNs outperformed traditional regression models in predicting changes in power requirements based on temperature, historical data, and customer behaviour (Almalaq & et al, 2017). Research by Gürbüz et al. (2019) found that ANN-based models enhanced energy distribution by reducing prediction errors in a smart grid application by 15-20%. ANNs are also commonly applied in a smart grid for problem detection and power quality analysis (Gürbüz, 2019). Research by Gil-González et al. (2020) indicates that ANN-based fault detection systems significantly enhance grid reliability by identifying faults within milliseconds (Gil-González & et al, 2020). Similarly, Haghnegahdar et al. (2018) found that ANN models achieved over 95% accuracy in detecting normal and problem states in the grid—outperforming conventional security systems. Smart grids also benefit from better integration of solar, wind, and hybrid power systems by utilizing artificial neural networks to predict power output and enhancing energy storage (Haghnegahdar & et al, 2020). Singh et al. (2021) found that ANN-based application in solar and

wind power prediction improved grid stability by reducing power fluctuations by up to 30%. Additionally, artificial neural network-based demand response strategies help shave peak loads and improve energy efficiency. Ali et al. (2023) demonstrated that ANN-based DSM systems minimized energy wastage by 18% through analysis of customer demand patterns and real-time power supply dynamics (Ali & et al, 2023). In summary, artificial neural networks have significantly advanced smart grids in demand response optimization, defect detection, renewable energy management, and energy forecasting. Previous research shows that ANN-based solutions can improve the performance of renewable energy, minimize energy losses, and maximize grid resilience.

5. Integration of Blockchain and Neural Networks in Smart Grids

Smart grids have attracted substantial interest due to the combination of blockchain technology and neural networks, as they present opportunities to enhance performance while strengthening protective measures and prediction capabilities. The combination of blockchain technology provides decentralized, transparent power transactions that remain tamper-proof, alongside neural networks that perform pattern recognition and detect anomalies, as well as automated grid environment decision processes. When smart grids employ this dual-technology framework, they optimize energy management functions and enhance real-time data processing features, while also improving cybersecurity protection standards. Blockchain and neural networks significantly enhance the security, predictive maintenance, and efficiency of the smart grid. The tamper-evident feature ensures integrity and privacy, utilizing a decentralized ledger of the blockchain that is secure from unauthorized access. Neural networks apply sophisticated data analysis to provide predictive maintenance with early failure detection and efficient resource allocation (Abdellatif & et al, 2025). For example, research has been dedicated to utilizing blockchain technology to ensure data integrity and security through the development of a distributed learning paradigm based on blockchain, aiming to enhance the efficiency and security of the smart grid. Moreover, studies prove that the convergence of blockchain technology with deep learning offers secure data exchange as well as intruder identification in smart grids. Smart grid operations are made safer, more reliable, and more efficient by such connections (Kumar & et al, 2023). The primary drawback of blockchain for smart grids is its slow processing speed and insufficient computational power when handling transactions. Neural networks enhance blockchain performance by optimizing consensus mechanisms, such as Proof of Work (PoW) and Proof of Stake (PoS), thereby reducing the power consumption required for transaction authentication (Ahmed et al., 2022). Using AI models for prediction helps determine transaction levels and optimize block validation uptime, thereby improving overall operational efficiency (Hafid et al., 2020). AI-cueled adaptive smart contracts enable the analysis of historical energy consumption data to inform pricing models in peer-to-peer (P2P) trading systems, thereby enhancing energy market responsiveness and reducing costs, as noted by Wu et al. (2022). The combination of predictive maintenance and artificial intelligence with blockchain technology allows data analysis of IoT sensors to authenticate maintenance records, thereby reducing grid failure risks and cyberattack threats (Almasoudi, 2023). The reliability of smart grids (Waseem et al., 2023) depends upon the implementation of these measures, as they stop man-in-the-middle (MITM) attacks, spoofing, and false data injection. Both blockchain technology and AI, when combined, can transform decentralized energy trading and predictive maintenance. Blockchain technology provides secure, transparent, and tamper-evident transactions, making it ideal for such use cases. Meanwhile, AI models are able to process vast amounts of grid data in real time and make more intelligent choices. Another common application is peer-to-peer (P2P) energy trading, in which the blockchain technology enables consumers and producers (prosumers) of energy to directly trade without an intermediary. The trading is executed by smart contracts, providing bilateral rates to both entities while introducing trust among stakeholders. Moreover, using blockchain's tamper-proof ledger with the anomaly detection function of AI escalates predictive maintenance levels significantly. For the detection of anomalies and anticipating any failure before it occurs, machine learning models analyse data from smart meters and grid assets. Storage of the outcome in a blockchain guarantees integrity of data and supports auditing and regulatory uses by tracing events. Such technologies transform the grid into an efficient grid, reduce operating expenses,

and increase the reliability of power. Real-world applications, such as Power Ledger's P2P platform and AI-aided maintenance in renewable energy farms, demonstrate the utility and feasibility of this synergy, paving the way for a more innovative and robust energy infrastructure.

Behavioral energy management receives important applications through the combination of AI and blockchain systems. The combination of AI models brings the ability to predict energy needs, which also includes optimizing demand distribution while simultaneously executing energy delivery in decentralized environments (Islam & et al, 2024). AI utilizes past and current electricity usage data to predict maximum usage periods for blockchain platform smart contracts, thereby optimizing power delivery efficiency. Demand response mechanisms benefit from enhancement through supply-demand-based price adjustments, which decrease consumer costs without destabilizing the power grid (Ferdous & et al, 2023). The effectiveness of uniting blockchain technology with AI within smart grids becomes clear through existing practical applications as follows:

- IBM and TenneT (Germany & Netherlands) created blockchain-powered AI prediction algorithms for managing decentralised power grid balance (Alotaibi & et al, 2020).
- LO3 Energy introduced their P2P energy trading initiative featuring AI predictive analytics that enables customers to reach energy efficiency in their usage (Wu & et al, 2022).
- The Australian technology company Power Ledger applied blockchain along with machine learning to boost distributed energy resource management to deliver more accessible and practical solutions (Treiblmaier, 2023).
- The EU H2020 Platone Project executed blockchain and AI technology to enhance energy storage operations and manage power demand, which created a stronger, adaptable power system (Khalid, 2024).

The implementation of blockchain and neural networks in smart grids encounters obstacles related to processing expenses as well as interface matters and regulatory adherence requirements. Escalation problems persist in artificial intelligence models that implement blockchain-based solutions, as noted by Hafid et al. (2020). Standardization of protocols together with data privacy concerns act as significant impediments to blockchain-based adoption throughout the industry (Ferdous & et al, 2023). Research needs to create light blockchain protocols and decentralized AI frameworks and energy-efficient neural networks for eliminating technological obstacles in modern energy systems (Javaid & et al, 2018).

Through their strategic union, blockchain technology holds promise as a secure and intelligent system that enhances the efficiency of smart grids. The details of present technical requirements and governing standards can transform energy control systems while creating paths for moving toward distributed renewable power networks.

5. 1. The Role of AI-driven Neural Networks in Improving the Scalability and Efficiency of Blockchain-based Smart Grid Systems

In Germany's Brooklyn Microgrid, peer-to-peer (P2P) energy trading based on blockchain and optimised by AI anticipates user demand and enables the transactions with increased efficiency and reduced latency. This ensures the effectiveness of integration between blockchain and artificial intelligence.

The State Grid Corporation of China applies neural networks to recognise patterns of energy transactions on a blockchain platform, detecting cyber-attacks and fraud in real time. AI neural networks offer groundbreaking solutions to scalability and efficiency issues in blockchain-based smart grids. Through consensus optimisation, computational efficiency improvement, and predictive maintenance assistance, AI enhances grid reliability and performance. Table 3 shows the comparison between Traditional Blockchain Smart Grid and AI-Driven Blockchain Smart Grid.

Table 3. Traditional Blockchain Smart Grids and AI-Driven Blockchain Smart Grids

Aspect	Traditional Blockchain Smart Grid	AI-Driven Blockchain Smart Grid
Transaction Speed	Slow due to high computational demand	Faster with AI-optimised consensus mechanisms
Energy Consumption	High, especially with PoW consensus	Reduced via reinforcement learning-based energy allocation
Data Management	Inefficient storage and retrieval	AI-enabled data compression and smart indexing
Security	Vulnerable to fraudulent transactions	AI-enhanced anomaly detection for real-time threat prevention
Predictive Capabilities	Limited to predefined algorithms	Advanced forecasting and automated grid optimisation

6. Challenges and Potential Solutions

The integration of blockchain and neural networks for intelligent grids is highly promising, offering improved repair prediction, enhanced efficiency, and increased security. Integration is not without issues, primarily related to interoperability, scalability, and computational complexity.

- Interoperability is a problem due to a difference in protocol and architecture between the distinct elements and parties of smart grids. It may hinder smooth data and system integration. To control it, utilizing a standardized communication protocol and developing middleware solutions to connect divergent technologies play significant roles (Belchior & et al, 2021). Such standardization contributes to seamless interactions between heterogeneous systems for intelligent and efficient operations in smart grids.
- Intensive processing required by blockchain's consensus algorithms and deep models in neural networks forms computational complexity. Such conditions can strain the computing resources of smart grid infrastructure. The solution for this problem is the application of federated learning. In this method, edge devices or local servers are trained using local models, and aggregated information is transmitted to a central system. This method reduces data transfer requirements, minimizing computational strain while maintaining data privacy.
- Scalability remains an issue, as blockchain networks have sometimes struggled with processing throughput in large smart grids (Ressi & et al, 2024). The blockchain architecture, in which each node verifies each transaction, can cause bottlenecks as the network expands in size. Sidechains and sharding have been suggested as potential scaling solutions for blockchain. Sidechains enable the offloading of transactions from the primary blockchain onto secondary parallel chains, thereby clearing up and increasing efficiency. Sharding is the division of the blockchain network into several small partitions (shards), each of which is capable of independently processing transactions, thus increasing overall processing capacity (Sanka & et al, 2021).

By effectively addressing such issues through utilizing standardized protocols, federated learning, and utilization of scalability technology such as sidechains and sharding, smart grids can be empowered to utilize the complete capabilities of the blockchain technology and neural networks. This convergence can enhance security, efficiency, and predictive maintenance ability in smart grids, ultimately leading to smarter and safer energy systems.

7. Results and Discussion

Research into blockchain and neural network implementation in smart grids highlights both promising features with their application and important difficulties they present. The analysed scholarly works indicate that blockchain technology strengthens electrical grid protection, shows all monetary transactions, and allows peer-to-peer electricity exchanges. Meanwhile, artificial intelligence enables better power usage management, improves fault identification systems, and creates forecasting capabilities

to stabilise the power network. Several critical problems still need resolution in this field because of high operational expenses, regulatory barriers, scalability limitations, and data compatibility problems. According to Prakash et al. (2022) and Almasoudi (2023), blockchain technology provides fundamental protection against cyber threats, including MITM attacks as well as spoofing activities and unauthorised data modification. Zhang et al. (2018) supported this concept by explaining that decentralised ledgers can both protect smart grids from data modification attempts and increase security measures. Blockchain encryption methods, however, face serious issues in terms of computational efficiency. Researchers have incorporated AI-based encryption measures in addition to fraud detection algorithms in designing blockchain security protocols which maintain high efficiency levels. AI-based prediction models, as mentioned by Javaid et al. (2018), demonstrate capability in analysing real datasets for predictive load balancing systems in addition to demand-side management, as noted by Ahmed et al. (2022). The deep learning protocols also show capacity in predicting energy demand variations, as investigated by Sun et al. (2019), yielding better efficiency in intelligent grids. The application of AI in real-time operations faces implementation issues, as mentioned by Islam et al. (2024), due to slow processing rates in addition to delayed operations. Research by Siano et al. (2020) indicates how edge computing, when applied to AI-smart contracts, resolves these issues by enhancing distributed energy management in real-time operations using decentralised infrastructure. The integration of blockchain technology allows intelligent grids to enable direct peer-to-peer (P2P) energy trading between prosumers. Alotaibi et al. (2020) and Wu et al. (2022) further reveal how blockchain-based energy markets improve power flexibilities by disrupting monopolies in energy supply by incumbents. The large-scale implementation of distributed energy markets meets network utilisation issues and complexity in regulation in conformity with Waseem et al. (2023). Research by Ferdous et al. (2023) and Hafid et al. (2020) ventures simplistic blockchain protocols and regulatory measures to address these implementation issues and develop standard blockchain integration in intelligent grids. Blockchain technology faces a significant scalability challenge, particularly in high-rate transactions within energy markets of intelligent grids. Treiblmaier (2023) and Khalid (2024) analyse how blockchain mining and consensus operations strain environmental resources. The application of Proof-of-Work (PoW) and Proof-of-Stake (PoS) mechanisms receives optimisations through the use of AI to mitigate energy requirements, as mentioned by Ahmed et al. (2022). Improved blockchain scalability is made using layer-2 blockchain implementations as mentioned by Hafid et al. (2020), while maintaining the same level in terms of computational efficacy. The implementation of blockchain technology and neural networks is a promising solution for developing a decentralized and less risky power distribution network. Efficient use of this network is possible only by solving scalability issues, improving calculation effectiveness, and outlining regulatory frameworks for processing real-time information of AI. Studies by Zhang and others in 2018, Sun and others in 2019, and Siano and authors in 2020 suggest three innovative solutions for overcoming common shortcomings in intelligent grids: AI-capable blockchain enhancements, decentralised networks of markets and edge-computing-based administration of power grids. Future investigations need to create lightweight blockchain systems that integrate real-time AI analytics with the establishment of worldwide regulatory frameworks to support practical and scalable deployment within smart grids. Table 4 shows the challenges identified in previous studies along with the proposed strategies and solutions in each reference.

Table 4. Comparison of Previous Studies on Blockchain and Neural Networks in Smart Grids

Reference	Objective	Results	Challenges	Proposed Solutions
Ahmed et al. (2022)	AI-driven blockchain optimisation in SG	AI can optimise PoW and PoS to reduce energy consumption and improve transaction speed	High computational cost	Adaptive AI-based consensus mechanisms
Almasoudi (2023)	AI-enhanced cybersecurity in SG	AI detects anomalies and prevents MITM, spoofing, and data injection attacks	Privacy concerns & regulatory challenges	Blockchain-based AI authentication & encryption

Alotaibi et al. (2020)	AI and blockchain in P2P energy trading	Smart contracts enable efficient, decentralised energy transactions	Scalability of blockchain for large-scale energy markets	AI-driven predictive load balancing
Ferdous et al. (2023)	Blockchain for renewable energy certificates	Distributed ledger improves traceability & transparency in energy trading	Standardisation & legal barriers	Regulatory frameworks for blockchain adoption
Hafid et al. (2020)	Scaling blockchain in smart grids	Layer-2 solutions can enhance transaction efficiency	Energy-intensive computations	Optimised lightweight blockchain protocols
Islam et al. (2024)	AI in smart grid stability and energy storage	AI predicts energy demand and prevents grid overload	Limited real-time implementation	AI-powered smart contracts for automated energy dispatch
Javaid et al. (2018)	AI-based DSM (Demand Side Management)	AI optimises demand-side response for SG efficiency	Data interoperability	Unified blockchain-based AI energy management
Khalid (2024)	Smart grid integration with blockchain & AI	Improved energy distribution through AI-enhanced smart contracts	Regulatory compliance	Blockchain governance frameworks for energy markets
Prakash et al. (2022)	AI-enhanced blockchain security	Text mining analysis on blockchain-based cybersecurity models	Complexity in implementation	AI-driven encryption and fraud detection models
Treiblmaier (2023)	Bitcoin's energy use in blockchain applications	AI improves energy efficiency in blockchain-based transactions	Environmental concerns	AI-driven energy-efficient mining protocols
Waseem et al. (2023)	Blockchain in various SG applications	AI-powered energy trading enhances efficiency and security	Network congestion issues	Distributed AI-assisted consensus mechanisms
Wu et al. (2022)	Blockchain & AI for microgrid management	Blockchain and AI enable collective energy balance and decentralised transactions	Cross-sector interoperability issues	Standardised blockchain interfaces for microgrids

8. Conclusion

Smart grids that adopt neural networks alongside blockchain acquire several capabilities to protect energy systems and enhance operational performance with decentralised power management functions. Blockchain technology united with AI capabilities enables data authentication, enhances systems visibility, lets peers conduct safe power purchases, and improves grid optimisation processes. Major obstacles emerge during large-scale implementation because they link with high computational expenses and regulatory barriers which create limitations to scalability. Energy trading transformation features various edge computing, advanced AI analytics, and lightweight blockchain design approaches that intend to reduce network delays and reinforce power distribution system reliability. Academic research in the future needs to work on blockchain infrastructure flexibility and the introduction of artificial intelligence data analytics in real-time operation along with standard regulatory frameworks. Smart grids operate sustainably at maximum efficiency through decentralised energy markets when implemented with innovative technologies that ensure secure operational efficiency of their energy system.

Data Sharing Statement

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Disclosure

The authors report no conflicts of interest for this work.

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آليات الحد من تغير المناخ: تكنولوجيا التقاط الكربون واستخدامه وتخزينه أنموذجا

Mechanisms to Limit Climate Change,Carbon Capture, Utilization and Storage Technology as a Model

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ABSTRACT

This study examines the definition of carbon capture, utilisation, and storage technology as one of the approved options for reducing greenhouse gas emissions, achieving carbon neutrality, and achieving net zero carbon emissions. It also analyses the stages and requirements of this technology, which, despite its importance, faces major challenges, most notably the high cost of its infrastructure and its environmental and health damages. The study also addressed the uses and prospects of this technology in the Gulf Cooperation Council countries. It concluded that carbon capture, utilisation, and storage (CCUS) technology is a promising technology for reducing carbon dioxide emissions. It requires the participation of various stakeholders and the establishment of a set of legal, regulatory, and economic frameworks. However, the high costs associated with its infrastructure and the environmental and health impacts it produces have been an obstacle to the widespread use of this technology worldwide. The recommendations included the need to establish legislative and regulatory f rameworks compatible with carbon capture, transport, and storage (CCUS) technology; encourage investment in carbon capture, transport, and storage (CCTS) projects by providing grants, soft loans, and tax exemptions; and enhance international and regional cooperation in the field of CCUS technology.The researcher relied on a plan that outlines the stages and requirements of carbon capture, utilisation, and storage technology in the first section and further examines the feasibility of this technology and its prospects in the Gulf Cooperation Council countries in the second section.

Keywords: Climate change, Carbon capture, Carbon utilisation, Carbon storage, Capacity building.

الملخص

تطرّقت هذه الدراسة إلى عرض تكنولوجيا التقاط الكربون واستخدامه وتخزينه باعتبارها من الآليات الحديثة المعتمدة للحد من انبعاثات الغازات الدفيئة وتحقيق هدف الحياد الكربوني، أي الوصول بصافي الانبعاثات إلى الصفر. كما تناولت مراحل تطبيق هذه التقنية ومتطلباتها المختلفة، مع الإشارة إلى التحديات التي تعيق انتشارها، وعلى رأسها التكلفة المرتفعة للبنية التحتية والتأثيرات البيئية والصحية المصاحبة لها. وناقشت الدراسة كذلك فرص استخدام هذه التكنولوجيا في دول مجلس التعاون الخليجي، واستشرفت آفاق تطويرها في المنطقة. وقد خلصت النتائج إلى أن تكنولوجيا التقاط الكربون واستخدامه وتخزينه تُعد من الحلول الواعدة في تقليل انبعاثات ثاني أكسيد الكربون، لكنها تتطلب تنسيقًا متعدد الأطراف وإرساء أطر قانونية وتنظيمية واقتصادية مناسبة. غير أن ارتفاع تكاليفها وما قد ينجم عنها من آثار جانبية بيئية وصحية يمثلان عائقًا حقيقيًا أمام تبنيها على نطاق واسع. وبناءً عليه، أوصت الدراسة بضرورة سن تشريعات مرنة تتماشى مع خصوصية هذه التكنولوجيا، وتحفيز الاستثمارات من خلال توفير الدعم المالي، كالقروض الميسرة، والمنح، والتسهيلات الضريبية، إلى جانب تعزيز التعاون الإقليمي والدولي في هذا المجال.اعتمد الباحث في هذه الدراسة على إطار منهجي يُبرز في المبحث الأول مختلف مراحل تكنولوجيا التقاط الكربون واستخدامه وتخزينه، إلى جانب متطلباتها الأساسية، بينما خُصص المبحث الثاني لتحليل الجدوى التطبيقية لهذه التقنية واستشراف آفاقها المستقبلية داخل دول مجلس التعاون الخليجي.

الكلمات المفتاحية: تغير المناخ، استخدام الكربون، تخزين الكربون، التقاط الكربون، بناء القدرات.

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المقدمة

يعاني كوكب الأرض من تفاقم ظاهرة التغير المناخي، ويُعد ثاني أكسيد الكربون الناتج عن الانبعاثات المرتبطة باستخدام الوقود الأحفوري – كالفحم، والنفط، والغاز الطبيعي – من أبرز العوامل المسببة لها. هذه الانبعاثات، الصادرة من وسائل النقل، المنشآت الصناعية، ومحطات توليد الطاقة، تتضمن ما يُعرف بالغازات الدفيئة، التي تمتص الأشعة تحت الحمراء المنبعثة من سطح الأرض وتُعيد إشعاعها، مما يؤدي إلى تصاعد ظاهرة الاحتباس الحراري وزيادة متوسط درجات الحرارة العالمية.[1]

في سياق الجهود العالمية لمواجهة مخاطر التغير المناخي، تم اعتماد اتفاقية باريس لسنة 2015، والتي تُعد حتى اليوم من أبرز المعاهدات الدولية المعنية بالتصدي لهذا التحدي البيئي. وتُلزم هذه الاتفاقية الدول الموقعة عليها باتخاذ إجراءات فعالة لخفض انبعاثات الغازات الدفيئة التي تسهم في ارتفاع درجات الحرارة على كوكب الأرض. ومن بين أهدافها الرئيسية تحقيق ما يُعرف بـ "الحياد الكربوني" أو "صافي الانبعاثات الصفرية" خلال النصف الثاني من القرن الحادي والعشرين، أي تحقيق توازن بين كميات الانبعاثات الصادرة وتلك التي يتم التخلص منها من الغلاف الجوي. كما تنص الاتفاقية على إجراء مراجعة دورية كل خمس سنوات لتقييم مدى التقدم المحرز نحو تحقيق أهدافها، ضمن آلية تُعرف باسم "التقييم العالمي". وفي هذا الإطار، برزت عدة تقنيات حديثة تهدف إلى تقليص انبعاثات الغازات الدفيئة إلى مستويات يمكن للنظم البيئية الطبيعية التعامل معها والتكيف مع تأثيراتها.

وفي هذا السياق، برزت تقنية احتجاز الكربون واستخدامه وتخزينه (CCUS) كأحد الحلول المبتكرة، حيث تعتمد على جمع غاز ثاني أكسيد الكربون الناتج عن العمليات الصناعية، ثم الاستفادة منه عبر تحويله إلى منتجات قابلة للتسويق والاستخدام التجاري.

عرّفت الوكالة الدولية للطاقة تقنية استخدام الكربون وتخزينه بأنها "عملية تهدف إلى احتجاز غاز ثاني أكسيد الكربون الناتج عن الأنشطة التي تعتمد على المواد الأولية الحيوية – مثل الكتلة الحيوية – لإنتاج الطاقة الحرارية أو الكهرباء أو الوقود الحيوي، ثم نقله وتخزينه بشكل آمن لمنع إطلاقه في الغلاف الجوي".

وقد قام فريق عمل الطاقة الحيوية مع احتجاز وتخزين الكربون، التابع لمنتدى القادة المعنيين بتقنيات احتجاز الكربون، بتعريف هذه التقنية على أنها "نهج يجمع بين استخدام مصادر الطاقة الحيوية بمختلف أشكالها – سواء لإنتاج الكهرباء أو الحرارة أو الوقود – وبين عمليات احتجاز ثاني أكسيد الكربون وتخزينه، بهدف تقليل الانبعاثات بشكل فعال".

أما لجنة التغير المناخي في المملكة المتحدة، فقد قدّمت تعريفًا لتقنية استخدام الكربون وتخزينه، باعتبارها أسلوبًا يعتمد على تحويل مصادر حيوية مثل الكتلة الحيوية، الغاز الحيوي، والنفايات ذات الأصل العضوي إلى طاقة – سواء كهرباء، حرارة، وقود، أو غاز الميثان – مع احتجاز انبعاثات ثاني أكسيد الكربون الناتجة عن هذه العمليات وتخزينها في تكوينات جيولوجية آمنة.

عرّفت الجمعية العالمية للغاز الحيوي تقنية استخدام الكربون وتخزينه على أنها "دمج بين إنتاج الطاقة وعمليات احتجاز وتخزين الكربون، حيث تُعالج النفايات العضوية داخل وحدات الهضم الحيوي، ويتم خلال هذه العملية التقاط غاز ثاني أكسيد الكربون الناتج، بهدف منعه من الوصول إلى الغلاف الجوي".[2]

تُستخدم تقنية احتجاز وتخزين الكربون في الولايات المتحدة الأمريكية منذ عام 1972، حيث نجحت منشآت معالجة الغاز الطبيعي في ولاية تكساس في التقاط كميات كبيرة من غاز ثاني أكسيد الكربون، تجاوزت 200 مليون طن، تم حقنها وتخزينها في طبقات جيولوجية تحت سطح الأرض.

بحسب تقرير المعهد العالمي لاحتجاز وتخزين الكربون الصادر عام 2022، بلغ عدد المشروعات الكبرى في هذا المجال على مستوى العالم 194 منشأة بحلول نهاية ذلك العام، مقارنة بـ51 فقط في عام 2019، مما يعكس نموًا ملحوظًا. وتوزعت هذه المشروعات جغرافيًا على النحو الآتي: 94 مشروعًا في الأمريكيتين، منها 80 في الولايات المتحدة وحدها، و73 في أوروبا، من بينها 27 في المملكة المتحدة، إضافة إلى 21 مشروعًا في منطقة آسيا والمحيط الهادئ، و6 مشروعات في منطقة الشرق الأوسط.

شهدت القدرة الإجمالية لاحتجاز ثاني أكسيد الكربون في المشروعات قيد التطوير نموًا ملحوظًا خلال عام 2022، حيث وصلت إلى 244 مليون طن سنويًا، مسجلة بذلك زيادة بنسبة 44% مقارنة بالعام السابق، ما يعكس تسارعًا كبيرًا في تبني هذه التقنية عالميًا.

يفيد المعهد العالمي لاحتجاز وتخزين الكربون بأن هذه التقنية قد أثبتت موثوقيتها، حيث يتم استخدامها بشكل آمن وفعّال منذ أكثر من 45 عامًا.[3]

أهمية الموضوع

يُعد التغير المناخي تحديًا عالميًا خطيرًا يهدد مستقبل الإنسانية، ويُعزى بدرجة كبيرة إلى انبعاثات غازات الكربون الناتجة عن الأنشطة الصناعية، ومحطات توليد الطاقة، ووسائل النقل. هذا الوضع يستدعي من المجتمع الدولي تطوير واعتماد حلول تكنولوجية مبتكرة للحد من هذه الظاهرة، ومن أبرز هذه الحلول تقنية التقاط الكربون ونقله واستخدامه وتخزينه، التي بدأ العديد من الدول في تطبيقها بهدف تقليص انبعاثات الغازات الدفيئة.

[1] مصطفى، سالم، العدالة المناخية في ضوء اتفاقية باريس لتغير المناخ، مجلة العلوم القانونية، 2023، ص23.
[2] مصطفى، سالم، العدالة المناخية في ضوء اتفاقية باريس لتغير المناخ، مجلة العلوم القانونية، 2023، ص23.
[3] التقرير العالمي لالتقاط الكربون وتخزينه لعام 2022.

إشكالية البحث

تُعد تقنية التقاط الكربون ونقله واستخدامه وتخزينه من الابتكارات الحديثة التي تلعب دورًا متزايد الأهمية في التخفيف من آثار التغير المناخي. وتتمحور الإشكالية الأساسية لهذا البحث حول دراسة المراحل المختلفة لتطبيق هذه التكنولوجيا، والمتطلبات اللازمة لنجاحها، بالإضافة إلى تقييم مدى جدواها واستشراف آفاق استخدامها في دول مجلس التعاون الخليجي.

تساؤلات البحث

وتتفرع عن الإشكالية الرئيسية مجموعة من التساؤلات الفرعية التي يسعى البحث إلى معالجتها، وهي كالآتي :

1. ما المقصود بتقنية التقاط الكربون واستخدامه وتخزينه (CCUS)؟
2. ما هي المراحل الأساسية التي تمر بها هذه التقنية؟
3. من هي الأطراف الفاعلة المشاركة في تطبيق هذه التكنولوجيا؟
4. ما الأطر القانونية والتنظيمية والمالية التي تؤطر استخدام هذه التقنية؟
5. ما أبرز المزايا التي تقدمها، وما التحديات التي تعيق انتشارها؟
6. كيف تبدو آفاق تطبيق هذه التكنولوجيا في دول مجلس التعاون الخليجي؟

أهداف البحث

تنبع أهمية هذه الدراسة من الطابع الحديث لتقنية التقاط الكربون واستخدامه وتخزينه، باعتبارها من أبرز الحلول الواعدة التي تهدف إلى تقليص الانبعاثات الغازية المسببة لظاهرة التغير المناخي. وقد أدى هذا الدور المحوري إلى جذب اهتمام متزايد من قبل الباحثين وصناع القرار والجهات المعنية بمواجهة تحديات المناخ كافة.

منهجية البحث

اعتمد الباحث في هذه الدراسة على توظيف أكثر من منهج علمي لضمان شمولية التحليل ودقته، حيث استند أولًا إلى المنهج الوصفي التحليلي القائم على الاستقراء والاستنباط؛ وذلك لتحليل تقنية التقاط الكربون واستخدامه وتخزينه من حيث مكوناتها، جدواها، متطلباتها، وآفاق تطبيقها في دول مجلس التعاون الخليجي. كما استعان بالمنهج المقارن من خلال دراسة تجارب عدد من الدول في هذا المجال، بهدف استخلاص أوجه الشبه والاختلاف وتحديد أفضل الممارسات.

الدراسات السابقة

- بريشي، بلقاسم، الحماية الدولية لمواجهة ظاهرة الاحتباس الحراري، كلية الحقوق والعلوم السياسية، مذكرة لنيل شهادة الماجستير، جامعة سيدي بلعباس، 2017-2018، وتتضمن دراسة للآليات الدولية لمواجهة ظاهرة تغير المناخ.

- مجدي، زينب، تغير المناخ في الدول العربية، بحث منشور في المجلة الدولية للسياسات العامة في مصر، 2023، و يستعرض آثار تغير المناخ والسياسات المتبعة في الدول العربية.

المبحث الأول: مراحل ومتطلبات تكنولوجيا التقاط الكربون واستخدامه وتخزينه

المطلب الأول: مراحل تكنولوجيا التقاط الكربون واستخدامه وتخزينه

الفرع الأول: التقاط الكربون

يُقصد بالتقاط الكربون، عملية فصل ثاني أكسيد الكربون المنبعث من محطات توليد الطاقة أو المنشآت الصناعية، وذلك بهدف الحد من تسربه إلى الغلاف الجوي وتقليل تأثيره على المناخ.[4]

توجد عدة طرق لالتقاط الكربون تتمثل في:

أولًا. التقاط الكربون من المصدر

يُطلق على إحدى تقنيات التقاط الكربون اسم "الالتقاط ما بعد الاحتراق"، وتُستخدم لتنقية غازات العادم المنبعثة من مداخن المنشآت الصناعية ومحطات الطاقة، من خلال فصل ثاني أكسيد الكربون عن باقي المكونات الغازية قبل إطلاقها في الجو. يمكن تنفيذ عملية التقاط الكربون من المصدر في ثلاث مراحل مختلفة: قبل الاحتراق، أو أثنائه، أو بعده، وذلك بحسب نوع الوقود والتقنية المستخدمة في إنتاج الطاقة أو العمليات الصناعية.[5]

1. التقاط الكربون قبل الاحتراق

تعتمد هذه التقنية على فصل الكربون من الوقود قبل عملية الاحتراق، وتُعرف بفعاليتها من حيث الكفاءة في تقليل الانبعاثات. غير أن تطبيقها العملي يقتصر على نوع محدد من محطات الطاقة يُعرف باسم "محطة الدورة المدمجة للتغويز (IGCC) "، ما يجعل استخدامها محدودًا من حيث الانتشار.

[4] Yoro KO, Daramola MO. Chapter 1—CO_2 emission sources, greenhouse gases, and the global warming effect. In: Rahimpour MR, Farsi M, Makarem MA, editors. Advances in carbon capture. Cambridge: Woodhead Publishing; 2020. p3–5.

[5] فيكرام فيشال، أتسوماسا ساكاي، بريا براساد، خوسيه بينيتيز توريس إنجفيلد اومبادزتفيدف، ريتشارد إسبوزيتو، جورج كوبرنا، باميال تومسكي ميسر بوك سبرينتس باربرا رولينج، أنا روكساس، التقاط الكربون و اسخدامه و تخزينه، كتيب لواضعي السياسات، 2004، ص 27-31.

2. التقاط الكربون بعد الاحتراق

ترتكز هذه التقنية على التقاط غاز ثاني أكسيد الكربون بعد احتراق الوقود، حيث يُفصل عن غازات المداخن الناتجة عن عملية الاحتراق، وذلك باستخدام أنظمة تنقية متخصصة قبل إطلاقها في الغلاف الجوي.

3. التقاط الكربون أثناء الاحتراق

تعتمد هذه التقنية على احتراق الوقود باستخدام الأكسجين النقي بدلًا من الهواء، مما يؤدي إلى توليد غازات مداخن تتكون أساسًا من ثاني أكسيد الكربون وبخار الماء، ما يُسهل عملية فصل الكربون لاحقًا.

ثانيًا. التقاط الكربون من الهواء مباشرة

تعتمد هذه التقنية على إزالة ثاني أكسيد الكربون مباشرة من الهواء المحيط، بدلاً من استخلاصه من مصدر الانبعاث. ويتم ذلك باستخدام أجهزة متخصصة تحتوي على مواد كيميائية قادرة على الارتباط بجزيئات ثاني أكسيد الكربون وفصلها عن الغلاف الجوي. ورغم أن هذه الطريقة تُعد من الحلول الواعدة في مواجهة التغير المناخي، إلا أنها ما تزال تواجه تحديات كبرى، وعلى رأسها ارتفاع التكاليف وكثرة استهلاك الطاقة.[6]

ومن الأمثلة البارزة على تطبيق تقنية الالتقاط المباشر من الهواء، قيام شركة النفط الأمريكية "أوكسيدنتال" بتطوير أكبر منشأة من هذا النوع بالقرب من عدد من حقول النفط في ولاية تكساس. كما أن شركة "Clime works" السويسرية قامت بإنشاء مشروع "Orca" بالقرب من العاصمة الآيسلندية ريكيافيك، والذي يُعد من المشروعات الرائدة عالميًا في مجال التقاط الكربون من الغلاف الجوي.

الفرع الثاني: نقل الكربون

بعد التقاط ثاني أكسيد الكربون، يُحوّل عادة إلى حالته السائلة تمهيدًا لنقله نحو مواقع التخزين المناسبة. ويتم النقل غالبًا عبر شبكات من الأنابيب البرية أو البحرية، وهي الوسيلة الأكثر استخدامًا نظرًا لانخفاض تكلفتها مقارنة بالوسائل الأخرى. ومع ذلك، قد تُسهم هذه العملية في انبعاثات كربونية إضافية ناتجة عن النقل ذاته. وتجدر الإشارة إلى أن الولايات المتحدة تعتمد هذه الوسيلة منذ قرابة خمسة عقود، حيث تمتلك شبكة تفوق 5000 ميل من خطوط الأنابيب المخصصة لهذا الغرض.

إلى جانب خطوط الأنابيب، يمكن أيضًا نقل ثاني أكسيد الكربون باستخدام وسائل أخرى مثل السكك الحديدية، وذلك عبر عربات صهريجية مضغوطة مصممة لنقل ثاني أكسيد الكربون في حالته السائلة، ما يتطلب تطوير بنية تحتية خاصة لهذا الغرض. كما يمكن استخدام السفن البحرية لنقل كميات كبيرة من الكربون، وقد شهدت اليابان في عام 2023، تدشين سفينة بسعة 1,450 مترًا مكعبًا مخصصة لنقل ثاني أكسيد الكربون المسال. وبالنسبة للمسافات القصيرة، تُستخدم الشاحنات كخيار عملي لنقل كميات محدودة من هذا الغاز.

الفرع الثالث: استخدام الكربون و تخزينه

1- الاستخدام

تشمل تقنيات استخدام الكربون إمكانية تحويل ثاني أكسيد الكربون إلى منتجات ذات قيمة مضافة، بدلًا من إطلاقه في الغلاف الجوي. ومن أبرز تطبيقاتها استخدام ثاني أكسيد الكربون في عمليات الاستخلاص المعزز للنفط واسترجاع الغاز عبر تقنيات متقدمة. كما يمكن تحويله إلى مجموعة متنوعة من المنتجات الصناعية، مثل مواد البناء، والخرسانة، وأسود الكربون، والألياف الكربونية، والبلاستيك، وغيرها من المواد التي تدخل في سلاسل القيمة الصناعية.

2- التخزين

تعتمد عملية تخزين ثاني أكسيد الكربون جيولوجيًا على حقنه في تكوينات أرضية مناسبة، مثل الخزانات النفطية والغازية المستنفدة، والتكوينات الجيولوجية الحاوية للمياه المالحة العميقة، بالإضافة إلى طبقات الفحم غير القابلة للاستخراج، وذلك بهدف عزله بشكل آمن وطويل الأمد عن الغلاف الجوي.[7]

المطلب الثاني: متطلبات تكنولوجيا التقاط الكربون واستخدامه وتخزينه

تتطلب تقنية استخدام الكربون وتخزينه تضافر جهود عدة جهات فاعلة، إلى جانب العمل على تطوير القدرات البشرية والتقنية (الفرع الأول)، كما تقتضي وجود أطر قانونية، تنظيمية، ومؤسساتية ملائمة لضمان نجاح تنفيذها (الفرع الثاني).

الفرع الأول: المشاركة وبناء القدرات

أولًا. المشاركة

تتطلب تكنولوجيا التقاط الكربون واستخدامه وتخزينه تعاونًا متعدد الأطراف، يشمل الجهات الآتية:

1. **صانعو السياسات:** يتمثل دورهم في وضع الإطار العام لتطوير هذه التقنية، من خلال دعم السياسات المشجعة للابتكار، وتعزيز التعاون بين القطاعين العام والخاص، إضافة إلى إشراك مختلف أصحاب المصلحة في عمليات صنع القرار.
2. **الجهات التنظيمية:** تضطلع بمهمة إعداد الأطر القانونية والتنظيمية اللازمة، ومراقبة تنفيذها، فضلًا عن مراجعة وإصدار التصاريح المتعلقة بالمشروعات.
3. **مطورو المشاريع:** يتولون مسؤولية تنفيذ المشروعات على الأرض، من خلال التخطيط، وتقييم أصحاب المصلحة، والتواصل الداخلي والخارجي لضمان قبول المجتمع ودعم الأطراف المعنية.

[6] طواهرية، منى، التغيرات المناخية ورهانات السياسة البيئية الدولية، مجلة اقتصاديات شمال افريقيا، 2020، ص27.

[7] المدهون، إبراهيم رباح، محاسبة الكربون ومخاطر التغيرات المناخية، مجلة المحاسب الفلسطيني، ديوان الرقابة الإدارية والمالية، 2023، ص57.

4. **المجتمع:** يُعد فاعلًا أساسيًا في هذه المنظومة، من خلال مشاركته في الحوارات المجتمعية، والمطالبة بالمعلومات، والتعبير عن المخاوف، والضغط على الجهات المختصة لضمان مراعاة الأبعاد البيئية والاجتماعية للتقنية.

وجدير بالذكر أن نجاح تنفيذ هذه التقنية بشكل آمن وفعّال يستلزم تفاعلًا وتنسيقًا مستمرًا بين جميع الأطراف المعنية، بما يضمن تبادل الخطط، وتشارك المعلومات، ومعالجة التحديات المشتركة.

ثانيًا. بناء القدرات

يتحقق بناء القدرات الضرورية لتطبيق تقنية التقاط الكربون واستخدامه وتخزينه من خلال عدة وسائل رئيسية، من بينها:

1. **التوعية بالمشروع**

وذلك عبر تنفيذ مشروعات ناجحة على أرض الواقع، وتنظيم حملات إرشادية وعروض توعوية لشرح أهمية التقنية وآلية عملها، بهدف تعزيز القبول المجتمعي والدعم المؤسسي.

2. **تأسيس شبكات قوية**

تهدف إلى تعزيز التعاون والتواصل بين مختلف الجهات المعنية بتنفيذ مشروعات التقاط الكربون، بما يضمن تبادل الخبرات وتنسيق الجهود بين الفاعلين.

3. **إنشاء مراكز متخصصة للاختبار والتدريب**

تتولى هذه المراكز مهام تطوير واختبار تقنيات الالتقاط والتخزين، إضافة إلى تدريب الكفاءات المستقبلية اللازمة لتشغيلها. فعلى سبيل المثال، أطلقت الهند في عام 2021، أول مركز وطني للتميز في هذا المجال، يُعنى بتطوير التصاميم المبتكرة، وتعزيز التعاون العلمي والتقني، وتوجيه جهود البحث والابتكار نحو تطبيقات فعالة لتقنية التقاط الكربون. ويعمل هذا المركز على تحويل ثاني أكسيد الكربون الملتقط إلى مواد كيميائية، إلى جانب استخدامه في عمليات الاستخلاص المعزز للنفط والغاز، مع التركيز على تطوير طرق منخفضة التكلفة ومستدامة.

4. **دعم واستثمار البحث والتطوير والانتشار**

يتعيّن على الدولة أن تضطلع بدور محوري في دعم البحث الأكاديمي المتخصص داخل الجامعات والمؤسسات التعليمية، بما يعزز الابتكار في مجال التقاط الكربون واستخدامه وتخزينه. كما ينبغي على الجمعيات العلمية والمهنية الكبرى في مجالات علوم الأرض والهندسة أن تنخرط في أنشطة بناء القدرات المتعلقة بهذه التقنية. ويشمل ذلك دعم برامج البحث والتطوير في أربعة محاور أساسية: تقنيات الالتقاط، مسارات الاستخدام، وسائل النقل، والحلول الجيولوجية أو التقنية للتخزين.[8] يساهم الاستثمار في البحث والتطوير والنشر العلمي في تعزيز جهود إزالة الكربون والحد من التأثيرات البيئية الناتجة عن الانبعاثات. ويتطلب هذا الاستثمار دعم التقنيات في مختلف مراحل التطوير، بدءًا من البحث الأساسي وصولًا إلى التطبيق العملي على نطاق واسع. ومن الضروري أن لا يُحصر هذا الجهد في مجال واحد فقط، بل يجب أن يشمل طيفًا واسعًا من التطبيقات، بما يساهم في تسريع تبني التكنولوجيا ونشرها كأداة فعّالة في تقليل الغازات الدفيئة.

5. **التدريب والتعليم**

يُعد تثقيف الأفراد وتدريبهم على تقنيات التقاط الكربون واستخدامه وتخزينه خطوة أساسية نحو بناء مستقبل مستدام. وفي هذا الإطار، أُنشئت المدرسة الصيفية الدولية متعددة التخصصات عام 2007، لتقديم برامج تدريبية مكثفة تمتد لأسبوع، تستهدف الباحثين والعلماء الراغبين في تعميق فهمهم لهذه التكنولوجيا. كما أطلق مكتب الطاقة الأحفورية وإدارة الكربون، التابع لوزارة الطاقة الأمريكية، منذ عام 2004، مبادرة "التجربة البحثية في عزل الكربون"، وهي برنامج تعليمي رائد يوجَّه إلى الطلاب والمهنيين، بهدف إعداد جيل جديد من المختصين القادرين على قيادة قطاع تقنيات الكربون والمساهمة في التحول نحو الطاقة النظيفة.

الفرع الثاني: توفير الأطر القانونية والمالية

يتطلب نجاح تكنولوجيا التقاط الكربون واستخدامه وتخزينه توفر بيئة تشريعية وتنظيمية داعمة، تشمل من جهة أولى **أطرًا قانونية وتنظيمية** واضحة (أولًا)، ومن جهة ثانية **أطرًا مالية واقتصادية** محفّزة (ثانيًا)، وذلك لضمان استدامة هذه المشروعات وتسريع تبنّيها على نطاق واسع.

أولًا. إقرار الأطر القانونية والتنظيمية

يتجسد الإطار القانوني والتنظيمي لتقنية التقاط الكربون واستخدامه وتخزينه في مجموعة السياسات، والتشريعات، والآليات القانونية التي تُعنى بدعم تطوير هذه الصناعة الناشئة، وضمان توافقها مع معايير حماية البيئة. وفي هذا السياق، من الضروري وضع أطر واضحة تشمل ما يلي:

1. ضبط معايير الأداء

- المعايير الوطنية

تُعرّف معايير الأداء باعتبارها أدوات تنظيمية تُلزم الشركات والمؤسسات الصناعية بخفض مستويات الانبعاثات الكربونية الناتجة عن أنشطتها. وتهدف هذه المعايير إلى دفع المؤسسات نحو تبني تقنيات أكثر كفاءة في استهلاك الطاقة وتقليل انبعاثات ثاني أكسيد الكربون. فعلى سبيل المثال، قد تقوم بعض الدول بسنّ معايير

[8] بنزايد، سارة، تأثير السياسة الطاقوية على تغير المناخ في إطار التنمية المستدامة، مجلة الريادة لاقتصاديات الأعمال، 2016، ص33.

محددة لقطاع صناعة السيارات، تُلزم الشركات المنتجة بتطوير مركبات تُظهر أداءً محسّنًا من حيث استهلاك الوقود، وتقليل الانبعاثات الناتجة عن عملية التشغيل.[9] وينطبق الأمر كذلك على فرض معايير خاصة بصناعة وتشغيل السيارات الكهربائية، التي تعتمد على الطاقة الكهربائية بدلًا من الوقود الأحفوري. وتمتاز هذه المركبات بعدة فوائد بيئية مقارنة بالسيارات المزودة بمحركات احتراق داخلي، من أبرزها تقليص التلوث الهوائي المحلي، نظرًا لعدم انبعاث ملوثات العادم منها، مثل المركبات العضوية المتطايرة، الهيدروكربونات، أول أكسيد الكربون، الأوزون، الرصاص، وأكاسيد النيتروجين بمختلف أنواعها.

- المعايير الدولية

تُعتمد المعايير الدولية من خلال توافق بين الدول الأعضاء ضمن إطار **المنظمة الدولية للتوحيد القياسي(ISO)** ، والتي تضم في عضويتها دولًا ومنظمات تمثيلية، يشارك عنها خبراء دوليون مختصون في مختلف المجالات. يتولى هؤلاء الخبراء إعداد وصياغة المبادئ التوجيهية الخاصة بكل معيار، قبل أن تُعرض على التصويت لاعتمادها رسميًا. ومن أبرز هذه المعايير ذات الصلة بتكنولوجيا التقاط الكربون واستخدامه وتخزينه، معيار **(ISO/TC 265)**، الذي أُنشئ عام 2011، ويُعنى بوضع المواصفات الفنية والتنظيمية لهذه التقنية، مما يساهم في توحيد الأطر المرجعية وتسهيل اعتمادها وتطبيقها داخل كل دولة.

2. اعتماد أُطر التحرك المبكر

والتي تتمثل في:

1. وضعَ الاتحاد الأوروبي إطارًا تشريعيًا لتخزين ثاني أكسيد الكربون منذ عام 2009، من خلال التوجيه **EC/2009/31** المتعلق بالتخزين الجيولوجي لثاني أكسيد الكربون، والذي يحدد القواعد الفنية والبيئية لضمان سلامة عمليات التخزين تحت الأرض. كما تم التنصيص على تكنولوجيا التقاط الكربون واستخدامه وتخزينه ضمن **قانون صناعة الحياد الصفري (Net-Zero Industry Act)**، باعتبارها من التقنيات الأساسية لتحقيق أهداف الاتحاد الأوروبي في خفض الانبعاثات الكربونية والوصول إلى الحياد المناخي.
2. يُعد برنامج الفئة السادسة للتحكم في الحقن تحت الأرض في الولايات المتحدة الأمريكية أحد المبادرات المهمة التي تهدف إلى حماية المصادر الجوفية لمياه الشرب من التأثيرات السلبية لأنشطة الحقن تحت الأرض. ويتم إدارة هذا البرنامج حاليًا على المستوى الفيدرالي، باستثناء ثلاث ولايات هي داكوتا الشمالية، وايومنغ ، ولويزيانا، حيث تدير هذه الولايات البرنامج بشكل مستقل.[10]
3. الإطار التنظيمي النموذجي للوكالة الدولية للطاقة: يُعد المثال المتعلق بالإطار التنظيمي للمسؤولية خلال مرحلة النقل من نقطة الانطلاق إلى موقع التخزين أحد الأمثلة المبكرة على تحديد المسؤوليات. وقد تضمن هذا الإطار ثلاث طرق رئيسية لمعالجة المسؤولية طويلة الأجل: إما من خلال تحميل السلطة المختصة المسؤولية، أو تحميل المسؤولية للمشغل، أو عدم التنصيص على المسؤولية طويلة الأجل بشكل صريح، وفي هذه الحالة يُفترض بالمشغل أن يتحمل المسؤولية عن موقع التخزين بشكل دائم. وتجدر الإشارة إلى أن قاعدة الفئة السادسة تتطلب رعاية الموقع بعد الحقن لمدة 50 عامًا، حيث يُلزم المشغل بمراقبة عمود ثاني أكسيد الكربون وضمان استمرار المسؤولية المالية.
4. تنص توجيهات الاتحاد الأوروبي المتعلقة بتقنية التقاط الكربون واستخدامه وتخزينه على تحميل المشغل مسؤولية موقع التخزين حتى مرحلة النقل، وهي فترة تمتد لمدة لا تقل عن 20 عامًا بعد توقف الحقن وإغلاق الموقع.

3. اعتماد الاتفاقيات الدولية

وتتمثل في:

1. اتفاقية الأمم المتحدة لقانون البحار لعام 1982: على الرغم من أن هذه الاتفاقية لم تنظم تقنية التقاط الكربون واستخدامه وتخزينه بشكل صريح، إلا أن المادة (210) منه تنص على أن إلقاء النفايات يُعتبر شكلًا من أشكال التلوث. كما تُلزم المادة (195) بعدم نقل الأضرار أو المخاطر، سواء بشكل مباشر أو غير مباشر، من منطقة إلى أخرى.
2. بروتوكول عام 1996 للاتفاقية المتعلقة بمنع التلوث البحري الناجم عن إلقاء النفايات والمواد الأخرى لعام 1972 (بروتوكول لندن): يُعد بروتوكول لندن معاهدة قانونية دولية شاملة تهدف إلى حماية البيئة البحرية، ويشمل البروتوكول (54) طرفًا متعاقدًا. ويحظر البروتوكول تصدير ثاني أكسيد الكربون للتخزين البحري، حيث يُعتبر ذلك بمثابة التخلص منه في البحر، مما يتعارض مع أهداف حماية البيئة البحرية.
3. اتفاقية بازل لعام 1989: تنص هذه الاتفاقية على ضرورة إخضاع التجارة الدولية في النفايات الخطرة للموافقة المسبقة أو الرفض من قبل الدول المتلقية، مما يضمن حماية البيئة والصحة العامة من المخاطر المحتملة الناتجة عن هذه النفايات.
4. اتفاقية بشأن تقييم التأثير البيئي في سياق عابر للقارات (اتفاقية أسبو): تضم الاتفاقية (45) طرفًا متعاقدًا، وتُلزم الأطراف بتقييم الآثار البيئية لأنشطتها العابرة للحدود خلال المراحل الأولى من تخطيط المشروع. ويخضع مشروع هذه التقنية لمقتضيات الاتفاقية إذا تم تنفيذها داخل أراضي الأطراف المتعاقدة أو من خلالهم.[11]

[9] A. Behfar, M. M. , Optimizing energy performance of a neighborhood via IMM® methodology: Case Study of Barcelona. NTERNATIONAL JOURNAL of ENERGY and ENVIRONMENT., 2013, p174.

[10] Carter, A. K. , Adaptation to climate change using green and blue infrastructure. University of Manchester, 2010,p85.

[11]Carter, A. K. , Adaptation to climate change using green and blue infrastructure. University of Manchester, 2010,52.

5. اتفاقية بشأن الوصول إلى المعلومات والمشاركة العامة في اتخاذ القرار والوصول إلى العدالة في الأمور البيئية (اتفاقية آرهوس): تضم هذه الاتفاقية (48) طرفًا متعاقدًا، وتُلزم الدول الأطراف بالامتثال لمتطلبات المشاركة العامة فيما يتعلق بالأنشطة التي قد يكون لها تأثير كبير على البيئة، مما يضمن شفافية أكبر ويعزز مشاركة المجتمع في اتخاذ القرارات البيئية.
6. اتفاقية باريس: تم إقرار اتفاقية باريس في عام 2015، وهي تُعد واحدة من أهم الاتفاقيات الدولية لمكافحة التغير المناخي على مستوى العالم. وقد شملت الاتفاقية مطالبة الدول الأطراف بخفض الانبعاثات المسببة لارتفاع درجات حرارة الأرض. وتنص على أن المتوسط العالمي لدرجات الحرارة يجب أن يبقى "أقل بكثير" من درجتين مئويتين فوق مستويات ما قبل الصناعة، مع التزام الدول بمواصلة جهودها للحد من ارتفاع درجات الحرارة إلى 1.5 درجة مئوية. كما تهدف الاتفاقية إلى تحقيق ما يُعرف بـ "الحياد الكربوني" أو "صافي صفر انبعاثات" في النصف الثاني من القرن الحالي، مما يعني توازن كميات الغازات الدفيئة المنبعثة مع تلك التي تمت إزالتها من الغلاف الجوي.
7. وتتضمن الاتفاقية أيضًا إلزام الدول بتقييم تقدمها كل خمس سنوات في ما يتعلق بتنفيذ أهداف الاتفاقية من خلال عملية تُعرف بـ "التقييم العالمي". كما توفر المادة (6) إرشادات أساسية لنقل تخفيض الانبعاثات بين الدول وتشجع القطاع الخاص على الاستثمار في الحلول البيئية المستدامة. وتقدم هذه المادة إطارًا جديدًا للتعاون عبر الحدود قائمًا على السوق، يتضمن آلية إئتمان مركزية جديدة تشبه آلية التنمية النظيفة.[12]

4. إصدار إستراتيجيات وتشريعات

من الضروري أن تقوم الجهات الحكومية بإصدار إستراتيجيات واضحة تحدد الخطوات التي تنوي الدولة اتخاذها لتطوير تقنيات التقاط الكربون واستخدامه وتخزينه. ويجب أيضًا إصدار التشريعات واللوائح المنظمة لهذه التقنيات، بالإضافة إلى تحفيز تطبيقاتها من خلال سياسات تدعم الابتكار والاستثمار في هذا المجال.

ثانيًا. إقرار الأطر المالية والاقتصادية

يتعين على الدولة تشجيع تكنولوجيا التقاط الكربون واستخدامه وتخزينه من خلال اتخاذ التدابير الآتية :

1. فرض ضريبة على الكربون

في إطار مكافحة الانبعاثات الدفيئة، وخاصة ثاني أكسيد الكربون، يجب على الدولة فرض ضريبة على الانبعاثات الكربونية وفقًا لحجمها وتأثيرها البيئي. وتهدف هذه الضريبة إلى تحفيز الشركات على الاستثمار في التقنيات منخفضة الكربون وتبني ممارسات أكثر استدامة. ففي عام 2012، أصدرت اليابان ضريبة على الكربون، بينما فرضت سنغافورة أيضًا ضريبة على الكربون في عام 2019، تبدأ من 5 دولارات للطن من مكافئات ثاني أكسيد الكربون، مع زيادة تدريجية تصل إلى 50-80 دولارًا للطن بحلول عام 2030.

في عام 2023، فرض الاتحاد الأوروبي ضريبة الكربون على المنتجات المستوردة ذات الانبعاثات الكربونية العالية، والمعروفة باسم **آلية تعديل حدود الكربون**. وتشمل هذه الضريبة منتجات مثل الحديد والصلب، والأسمنت، والأسمدة، والألومنيوم، والكهرباء، والهيدروجين، بهدف تقليل التأثير البيئي للمنتجات المستوردة إلى الاتحاد الأوروبي وتشجيع الصناعات العالمية على تبني ممارسات أكثر استدامة.

2. الإعفاءات الضريبية على الاستثمار والإعفاءات الضريبية على الإنتاج

في إطار تشجيع اعتماد تكنولوجيا التقاط الكربون واستخدامه وتخزينه، تقوم الدولة بمنح إعفاءات ضريبية للشركات المتخصصة في هذا المجال. ففي كندا، على سبيل المثال، تم الإعلان في تشرين الثاني/نوفمبر 2023، عن برنامج للإعفاء الضريبي على الاستثمارات في **CCUS** (التقاط الكربون واستخدامه وتخزينه)، حيث تم تحديد الإعفاء الضريبي بنسبة 50% للاستثمارات في هذه التكنولوجيا، وبنسبة 37.5% للمعدات المستخدمة في نقل وتخزين الكربون.[13]

وفي الولايات المتحدة الأمريكية، يُعد **الإعفاء الضريبي الموسع 45 Q** الذي تم تقديمه في عام 2018، من الحوافز المهمة لتشجيع تخزين ثاني أكسيد الكربون. كما قدم **قانون الحد من التضخم الأمريكي** لعام 2022، إعفاءً ضريبيًا قدره 50 دولارًا لكل طن متري من ثاني أكسيد الكربون يتم التقاطه باستخدام تقنيات التقاط واستخدام وتخزين الكربون، مما يعزز من تبني هذه التكنولوجيا على نطاق واسع.

3. تحديد نظام التجارة بالانبعاثات

يحدد هذا النظام الحد الأقصى لحجم الانبعاثات المسموح بها من خلال تخصيص حصص انبعاثات يتم التعبير عنها كبدلات. على سبيل المثال، نص **نظام تداول الانبعاثات** للاتحاد الأوروبي على تحديد حد أقصى إجمالي للانبعاثات المسموح بها، حيث يتعين على الجهات المصدرة للانبعاثات دفع بدلات تبادل الانبعاثات الخاصة بها. وإذا كانت الانبعاثات أقل من المسموح به، يتيح هذا النظام للباعثين إمكانية تداول الكميات الزائدة إلى بواعث أخرى. كما تقوم الدولة بشراء المنتجات الكربونية المنخفضة من محطات التقاط الكربون وتخزينه، دعمًا لهذه التكنولوجيا.

[12] Capture Utilisation and Storage CCUS dans la transition énergétique, Association Evenement Ose,Presse des Mines, le role du carbon ,2022,p75.

[13] Carter, A. K. , Adaptation to climate change using green and blue infrastructure. University of Manchester, 2010 ,p53.

4. تحفيز البحث والتطوير والنشر

من بين الوسائل التي تساهم في تحفيز نشر تكنولوجيا التقاط الكربون وتخزينه، تقوم الدولة بتشجيع أنشطة البحث والتطوير والنشر العلمي. وقد عمل العديد من الدول مثل الولايات المتحدة، وأوروبا، وكندا، وأستراليا، واليابان، على توفير برامج بحث وتطوير تهدف إلى تسريع نشر هذه التكنولوجيا وتعزيز استخدامها في مختلف القطاعات، مما يسهم في تطوير حلول مبتكرة للتحديات البيئية المرتبطة بتغير المناخ.[14]

5. إنشاء بنوك التنمية متعددة الأطراف

تقوم بنوك التنمية متعددة الأطراف، مثل **بنك التنمية الآسيوي** و**مجموعة البنك الدولي**، بتوفير موارد متنوعة للبلدان النامية بهدف تطوير البنية التحتية لتقنيات التقاط الكربون واستخدامه وتخزينه. تشمل هذه الموارد منحًا لدعم دراسات الجدوى وصياغة السياسات ذات الصلة، بالإضافة إلى إنشاء منشورات لتبادل المعرفة، وتقديم قروض ميسرة، وإنشاء صناديق خاصة لجذب تمويل الكربون.

6. مبادرات التعويض الكربوني

تهدف هذه المبادرات إلى تعويض الانبعاثات الكربونية من خلال استثمار الأموال في مشروعات تهدف إلى تقليل الانبعاثات وإزالة ثاني أكسيد الكربون، مثل زراعة الأشجار، واستخدام الطاقة المتجددة، وتطوير تقنيات التقاط الكربون واستخدامه وتخزينه.

7. منح القروض والضمانات المالية

تساعد هذه المبادرات في توفير التمويل اللازم لمشروعات التقاط الكربون واستخدامه وتخزينه، وهي شائعة في الولايات المتحدة الأمريكية، حيث يُعد **مكتب القروض** التابع لوزارة الطاقة أحد الأمثلة البارزة. يوفر هذا المكتب دعمًا ماليًا من خلال **قانون تمويل وابتكار البنية التحتية لوسائل نقل ثاني أكسيد الكربون**، ويعمل بالتعاون مع إدارة الطاقة الأحفورية والكربون، بالإضافة إلى **مكتب برامج القروض** التابع لوزارة البيئة. وفي آسيا، تم إنشاء صناديق ذات صلة بتغير المناخ، مثل **صندوق تحفيز العمل المناخي** التابع لبنك التنمية الآسيوي و**صندوق اليابان** التابع للحكومة اليابانية، والتي تدعم الاستثمار في تطوير مشاريع التقاط الكربون وتخزينه.[15] تم إنشاء العديد من **البنوك الخضراء**، وهي مؤسسات مالية متخصصة تهدف إلى تسريع الانتقال نحو اقتصاد منخفض الكربون. تقدم هذه البنوك قروضًا، وضمانات، وأنواعًا أخرى من التعزيزات الائتمانية لدعم وتطوير مشروعات الطاقة المتجددة، ومشروعات خفض الاحتباس الحراري، مثل تقنيات التقاط الكربون واستخدامه وتخزينه. ومن خلال هذا الدور، تساهم البنوك الخضراء في تطوير سوق الطاقة النظيفة والتكنولوجيا المستدامة، كما تشجع على الابتكار والتطوير في هذا المجال.

8. نشاء أسواق المنتجات منخفضة الكربون

إن إنشاء أسواق للمنتجات منخفضة الكربون يُعد خطوة حيوية في تسريع تطوير تكنولوجيا التقاط وتخزين الكربون. تشمل هذه المنتجات الإسمنت منخفض الكربون، والصلب، والمواد الكيميائية، وغيرها من المنتجات الصناعية التي يمكن أن تساهم في تقليل الانبعاثات الكربونية، مما يعزز من تبني تقنيات أكثر استدامة في مختلف القطاعات.

9. الكشف والإبلاغ عن الكربون

يتعين على الشركات أن تتحلى بالشفافية في الكشف عن انبعاثات غازات الدفيئة والإبلاغ عنها. على سبيل المثال، تفرض سويسرا على الشركات ذات الانبعاثات العالية مثل مصانع الإسمنت، والمواد الكيميائية، ومحطات الطاقة، المشاركة في **نظام تداول الانبعاثات** التابع للاتحاد الأوروبي. تحصل هذه الشركات على نقاط عندما تلتزم بمستويات محددة لانخفاض الانبعاثات، وتقوم بتداول هذه النقاط فيما بينها، مما يساهم في إنشاء سوق للانبعاثات. كما يُسمح للشركات متوسطة الحجم بالمشاركة طواعية في هذا النظام. في الهند، يُطلب من أكثر من 1000 شركة مدرجة في البورصة تقديم تقارير مفصلة عن انبعاثاتها.[16]

10. إنشاء أسواق الكربون

توفر **أسواق الكربون** نظامًا لتداول الانبعاثات عبر تصاريح أو شهادات تُعرف باسم **أرصدة الكربون**. يعادل كل رصيد كربون طناً واحداً من ثاني أكسيد الكربون أو ما يعادله من مكافئات ثاني أكسيد الكربون من غازات الدفيئة المختلفة التي تم تقليصها أو إزالتها أو تجنبها. تعمل هذه الأسواق وفقاً لمبدأ العرض والطلب، حيث يزداد الطلب على أرصدة الكربون من قبل الشركات والأفراد الذين يسعون طواعية لتعويض انبعاثات غازات الدفيئة عبر شراء الأرصدة. وتقوم جهات حكومية ومستقلة بإصدار هذه الأرصدة والتحقق من صحتها، مثل **فيرا**، **غولد ستاندرد**، **كلايمت أكشن ريسيرف**، و**سجل الكربون الأمريكي**.

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[14] Yoro KO, Daramola MO. Chapter 1—CO_2 emission sources, greenhouse gases, and the global warming effect. In: Rahimpour MR, Farsi M, Makarem MA, editors. Advances in carbon capture. Cambridge: Woodhead Publishing; 2020. p. 3–28.

[15] الحديثي، أنمارصلاح عبد الرحمن، الالتزام الدولي بحماية المناخ، منشورات الحلبي الحقوقية، الطبعة الأولى، 2016، ص76.

[16] J.L. Fan, S. Shen, M. Xu, Y. Yang, L. Yang, X. Zhang, Cost-benefit comparison of carbon capture, utilization, and storage retrofitted to different thermal power plants in China based on real options approach, Adv Clim Chang Res, 11 (4) (2020), pp. 415-428.

المبحث الثاني: جدوى تكنولوجيا التقاط الكربون واستخدامه وتخزينه وآفاقه في بلدان مجلس التعاون الخليجي

تتطلب تكنولوجيا التقاط الكربون واستخدامه وتخزينه دراسة جدواها (المطلب الأول)، وآفاقها في دول مجلس التعاون الخليجي (المطلب الثاني).

المطلب الأول: جدوى تكنولوجيا التقاط الكربون واستخدامه وتخزينه

تُوفر تكنولوجيا استخدام الكربون وتخزينه العديد من المزايا (الفرع الأول)، إلا أنها تواجه بعض العقبات التي تعيق تطبيقها على نطاق واسع (الفرع الثاني).

الفرع الأول: مزايا استخدام الكربون وتخزينه

تتمثل مزايا هذه التكنولوجيا في فوائد بيئية (أولًا)، وفوائد اقتصادية (ثانيًا).

أولًا.الفوائد البيئية

تساهم تكنولوجيا التقاط الكربون وتخزينه في تقليص انبعاثات الغازات المسببة للاحتباس الحراري والبصمة الكربونية. حيث تقوم هذه التكنولوجيا بحجز كميات ضخمة من ثاني أكسيد الكربون على مر الزمن، مما يساهم في تقليل الانبعاثات الضارة. علاوة على ذلك، فإن حقن ثاني أكسيد الكربون في خزانات النفط يتيح تخزين الكربون الذي كان يمكن أن يُطلق في الغلاف الجوي.[17]

في حال الانتشار الواسع لمشروعات التقاط الكربون واستخدامه وتخزينه، يمكن تقليص الانبعاثات السنوية بمقدار 20 مليار طن بحلول عام 2050، وهو ما يعادل أكثر من نصف الانبعاثات العالمية الناتجة عن حرق الوقود الأحفوري في الوقت الحالي.[18]

ثانيًا. الفوائد الاقتصادية

وتتمثل في:

1. الاستخلاص المعزز للنفط

تعتمد هذه التقنية على حقن ثاني أكسيد الكربون في خزانات النفط تحت الأرض لزيادة الضغط وتقليل لزوجة الزيت، مما يسهل عملية استخراجه. يساعد استخدام ثاني أكسيد الكربون في الاستخلاص المعزز للنفط على تحسين كفاءة استخراج النفط وزيادة القدرة على استخراج كميات إضافية كانت قد تبقى غير مستغلة، مما يساهم في رفع إجمالي الإنتاج. وقد أظهرت تقنيات الاستخلاص المعزز باستخدام ثاني أكسيد الكربون قدرتها على زيادة معدل الاسترداد بنسبة تتراوح بين 20-40% مقارنة بالطرق التقليدية، مما يجعلها تقنية مطلوبة في صناعة النفط والغاز. تركز الشركات على تطبيق هذه التقنية لزيادة الإنتاج في الحقول إلى أقصى حد، مما يعزز أرباحها. على سبيل المثال، حقل ويبورن ميدال في كندا يمثل مثالًا ناجحًا في تطبيق هذه التقنية، حيث شهد الحقل انخفاضًا كبيرًا في انبعاثات ثاني أكسيد الكربون مع زيادة في الإنتاج بنسبة تراوحت بين 10-15%.

تسهم هذه التقنية في إطالة العمر الاقتصادي لحقول النفط، بالإضافة إلى دورها في احتجاز ثاني أكسيد الكربون داخل التكوينات الصخرية تحت الأرض، مما يساعد على تقليل انبعاثاته إلى الغلاف الجوي.

من المبادرات البارزة في هذا المجال، مشروع الاستخلاص المعزز للنفط باستخدام ثاني أكسيد الكربون الذي نفذته شركة نفط الكويت في حقل المناقيش غرب الكويت، والذي أسهم في زيادة عامل الاستخلاص للنفط بنسبة 10%. كما قامت شركة أرامكو السعودية بتطبيق تكنولوجيا التقاط واستخدام الكربون وتخزينه في توليد الطاقة المحلية وفي قطاعات أخرى، حيث استخلصت نحو 99% من إجمالي الغاز المنتج وقلصت انبعاثات ثاني أكسيد الكربون بأكثر من 98 مليون طن متري سنويًا. بالإضافة إلى ذلك، قامت قطر بإنشاء أكبر مرفق لاحتجاز الكربون وتخزينه في منطقة الشرق الأوسط وشمال إفريقيا.

2. استخراج الغاز بأساليب متطورة

يتم ذلك عن طريق حقن ثاني أكسيد الكربون في أسفل مكمن الغاز المستفد، مما يساهم في دفع الغاز الطبيعي نحو آبار الإنتاج، ما يعزز من كفاءة استخراج الغاز.

3. استخلاص الميثان المحسن من طبقات الفحم الحجري

يتم ذلك عن طريق ضخ ثاني أكسيد الكربون في طبقات الفحم الحجري، حيث يقوم بإزاحة أي غاز متبقٍ في هذه الطبقات، مما يسهل استخراج الميثان. ومع ذلك، تجدر الإشارة إلى أن تكنولوجيا استخدام الكربون وتخزينه في مجالات الاستخلاص المعزز للنفط أو الغاز لا تفيد سوى صناعة الوقود الأحفوري، مما يعود بالضرر على المجتمع بشكل عام من خلال استمرار الاعتماد على مصادر الطاقة الملوثة.[19]

4. تحويل ثاني أكسيد الكربون إلى منتجات أخرى

يمكن استخدام ثاني أكسيد الكربون في تصنيع منتجات متنوعة مثل مواد البناء والخرسانة، بالإضافة إلى أسود الكربون، ألياف الكربون، والبلاستيك. كما يُستخدم في عملية التخمير في مصانع الجعة لإنتاج المشروبات، وكذلك في إنتاج الكربونات مثل بيكربونات الصوديوم التي تُستخدم في صناعة الأدوية والأغذية. يمكن أيضًا الاستفادة من ثاني أكسيد الكربون في استخراج الميثانول لاستخدامه كوقود للطائرات أو تحويله إلى مكونات وقود أخرى، أو في الصناعات الكيميائية. يُستخدم الجرافيت المصنوع من الكربون في تصنيع المحركات الكهربائية، أجهزة التنفس الاصطناعي، وقلم الرصاص. كما تُستخدم ألياف الكربون خفيفة الوزن في صناعة الطائرات،

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[17] طواهرية، منى، التغيرات المناخية ورهانات السياسة البيئية الدولية، مجلة اقتصاديات شمال إفريقيا، 2020، ص77.

[18] عبد الهادي نجار، احتجاز الكربون واستخدامه... سوق تدر مئات المليارات وتخفض الانبعاثات، صحيفة الشرق الأوسط، 9 أكتوبر 2022.

[19] المدهون، إبراهيم رباح ، محاسبة الكربون ومخاطر التغيرات المناخية، ص33.

الصواريخ، السكك الحديدية، والأدوات الرياضية. بالإضافة إلى ذلك، يُستخدم الكربون في صناعة الصفائح الجرافيتية الرقيقة داخل الأجهزة الإلكترونية، وصناعة الدهانات، الحبر، البطاريات، والإطارات المطاطية.

5. معالجة وتحلية المياه

يمكن استخدام ثاني أكسيد الكربون في معالجة وتحلية المياه لجعلها صالحة للاستهلاك البشري. في هذه العملية، يتم استخدام الكربون المنشط الحبيبي لإزالة الملوثات والشوائب عبر الامتصاص الكيميائي. تقوم آلية عمل الفحم المنشط الحبيبي على امتصاص المواد مثل الكلور، مركبات الرائحة، المبيدات الحشرية، الأعشاب الضارة، وغيرها من الملوثات العضوية. أظهرت الدراسات أنه عند معالجة المياه الجوفية باستخدام الكربون المنشط الحبيبي، تصبح المياه صافية تمامًا، حيث يمكن إزالة ما يصل إلى 3.60 و2.55 ملغ من الحديد والمنغنيز لكل غرام من الكربون. وقد تم تطبيق هذه التقنية في عدة دول كجزء من برامج لتحلية المياه، مثل جزر الأنتيل الهولندية، حيث توفر هذه التقنية 50% من مياه الجزيرة.

6. التدفئة والتبريد

يمكن استخدام ثاني أكسيد الكربون في أنظمة التدفئة والتبريد للمنازل بدلاً من المياه. وقد تم تنفيذ أول نموذج تجريبي في العالم لشبكة حرارية تستخدم ثاني أكسيد الكربون في مركب "إنرجي بوليس" بمدينة سيون في سويسرا.

الفرع الثاني: عقبات قائمة

تواجه تكنولوجيا التقاط الكربون واستخدامه وتخزينه عدة عقبات، تتمثل في ارتفاع التكلفة والصعوبات التقنية (أولاً)، بالإضافة إلى الأضرار البيئية المحتملة (ثانياً).

أولًا. تكاليف مرتفعة وصعوبات تقنية

1. تكاليف مرتفعة

تُعد تكنولوجيا التقاط الكربون وتخزينه من التقنيات المكلفة، حيث تتطلب استثمارات ضخمة في إنشاء مرافق الالتقاط وتطوير البنية التحتية اللازمة لنقل وتخزين ثاني أكسيد الكربون. إضافة إلى ذلك، تحتاج هذه التقنية إلى كميات كبيرة من الطاقة. وفي العديد من القطاعات، خاصة قطاع الكهرباء. تُعد الطاقة المتجددة أكثر اقتصادية من الوقود الأحفوري. لذا، من الأفضل تخصيص الميزانيات الكبيرة لدعم مشروعات إنتاج الطاقة النظيفة. وفقًا لوكالة الطاقة الدولية، تتراوح تكلفة التقاط وتخزين الكربون بين 20 و 150 دولارًا أمريكيًا لكل طن متري. في بعض الدول مثل كندا والنرويج، تم تعليق بعض المشروعات المتعلقة بتكنولوجيا التقاط الكربون بسبب الصعوبات المالية.[20]

في الولايات المتحدة الأمريكية، تم إغلاق مشروع بقيمة مليار دولار يهدف إلى استغلال انبعاثات ثاني أكسيد الكربون في مصنع فحم بولاية تكساس بسبب مشاكل ميكانيكية. ومع ذلك، من المتوقع أن تنخفض تكاليف هذه التقنية مع بدء تشغيل المزيد من المشروعات ، وتحسن التكنولوجيا، وتراجع تكاليف التمويل. ذلك يتم من خلال البحث والتطوير بهدف تقليل التكاليف وجعل هذه التقنية أكثر كفاءة من الناحية الاقتصادية.[21]

2. صعوبات تقنية

تواجه هذه التكنولوجيا تحديات تقنية كبيرة، إذ إن تصميمها معقد ويتطلب دمج العديد من المكونات المتنوعة المخصصة لتطبيقات معينة. فعملية التقاط الكربون من حقل نفط تختلف بشكل كامل عن تلك المخصصة لالتقاط الكربون وتخزينه في مصانع إنتاج الإسمنت، مما يتطلب تكييف تقنيات وطرق مختلفة لكل حالة على حدة.

ثانيًا. أضرار بيئية محتملة

تنتج التأثيرات البيئية المتعلقة بتقنية التقاط الكربون واستخدامه وتخزينه أثناء عمليات التقاط ثاني أكسيد الكربون، نقله، وتخزينه. قد يحدث تسرب للغاز بتركيزات مرتفعة، مما يسبب آثارًا صحية وبيئية خطيرة. ورغم أن هذه التكنولوجيا تهدف إلى تقليل انبعاثات الكربون، إلا أنها قد تسهم في زيادة استهلاك الوقود الأحفوري إذا لم تتم إدارتها بشكل صحيح.

من الجدير بالذكر أن العديد من الشركات التي تعتمد على الوقود الأحفوري تستخدم تقنية التقاط الكربون واستخدامه وتخزينه لتعزيز قدرتها الإنتاجية، وهو ما يتناقض مع الأهداف العالمية لمكافحة تغير المناخ. إذ إن هذه التقنية قد تساهم في استمرارية استخدام الوقود الأحفوري بدلًا من التوجه نحو مصادر طاقة أكثر استدامة. تُثار أيضًا مخاوف بشأن مدى أمان وفعالية تقنية استخدام الكربون وتخزينه تحت الأرض، خاصة فيما يتعلق بتسربه إلى الغلاف الجوي. إذ يوجد خطر في أن تتعرض أنابيب نقل الكربون للتلف، مما يؤدي إلى تسربه. على سبيل المثال، تم إلغاء مشروع خط أنابيب لالتقاط وتخزين الكربون في الولايات المتحدة الأمريكية، الذي كان يهدف إلى نقل الكربون من مصانع الإيثانول في وسط البلاد إلى مواقع التخزين المناسبة، وذلك بسبب المخاوف التي أبدتها المجتمعات المحلية بشأن احتمال تسرب الكربون.[22]

[20] الحديثي، أنمارصلاح عبد الرحمن، الالتزام الدولي بحماية المناخ، منشورات الحلبي الحقوقية، الطبعة الأولى، 2016، ص79.

[21] S. Kim, H. Shi, J.Y. Lee , CO_2 absorption mechanism in amine solvents and enhancement of CO_2 capture capability in blended amine solvent,Int J Greenh Gas Control, 45 (2016), pp. 181-188.

[22] طواهرية، منى، التغيرات المناخية ورهانات السياسة البيئية الدولية، ص44.

المطلب الثاني: آفاق تكنولوجيا التقاط الكربون واستخدامه وتخزينه في دول مجلس التعاون الخليجي

للمساهمة في الحد من ظاهرة الاحتباس الحراري، قامت عدة دول في المنطقة بتطوير قوانين بيئية. ففي البحرين، تم إصدار القانون رقم 7 لسنة 2007، بشأن البيئة في 25 آذار/مارس 2022. بينما تبنت دولة الإمارات العربية المتحدة قانونًا اتحاديًا لحماية البيئة وتنميتها في عام 1999. أما سلطنة عُمان فقد اعتمدت قانون حماية البيئة ومقاومة التلوث في عام 2001. وفي الكويت، تم إقرار قانون حماية البيئة في عام 2014. كما أصدرت المملكة العربية السعودية قانون نظام البيئة في عام 2019، في حين قامت قطر بإقرار قانون حماية البيئة في عام 2002.

قامت دول مجلس التعاون الخليجي بإدراج تكنولوجيا التقاط الكربون واستخدامه وتخزينه بشكل صريح ضمن سجل المساهمات المحددة وطنياً بموجب اتفاقية الأمم المتحدة الإطارية لتغير المناخ، حيث تعهدت البحرين بتخفيض الانبعاثات بنسبة 30% بحلول عام 2035. وأعلنت المملكة العربية السعودية والإمارات العربية المتحدة وسلطنة عُمان عن أهدافها لتحقيق صافي انبعاثات صفري في أعوام 2050 و2060 على التوالي. أما قطر فقد تعهدت بتخفيض الانبعاثات بنسبة 25% بحلول عام 2030. وتسعى الكويت إلى خفض انبعاثات الغازات الدفيئة بنسبة تصل إلى 80% بحلول عام 2040. كما تطمح سلطنة عُمان إلى تقليل انبعاثات الغازات الدفيئة بنسبة 7% بحلول عام 2030 والوصول إلى الحياد الكربوني بحلول عام 2050. وحتى آذار/مارس 2024، بلغ إجمالي عدد مشروعات التقاط الكربون واستخدامه وتخزينه المخططة في دول مجلس التعاون الخليجي 13 مشروعًا.

تم إنشاء العديد من مشروعات التقاط الكربون واستخدامه وتخزينه في دول مجلس التعاون الخليجي. ففي قطر، تقوم شركة "قطر غاز" باحتجاز 2.2 مليون طن سنويًا من غاز ثاني أكسيد الكربون من محطة تسييل الغاز في رأس لفان، وتسعى الشركة لرفع هذا المعدل إلى 5 ملايين طن سنويًا بحلول عام 2025. كما تحتجز شركة "قطر للوقود" 0.2 مليون طن سنويًا من غاز الكربون في مصفاة الميثانول. وفي المملكة العربية السعودية، تحتجز شركة "أرامكو" 0.8 مليون طن سنويًا من غاز الكربون في معمل غاز الحوية، حيث يُستخدم الغاز في الاستخلاص المعزز للنفط في حقل نفط العثمانية. أما الشركة السعودية للصناعات الأساسية، فـ تحتجز 0.5 مليون طن سنويًا من الكربون في منشأة الإثيلين في الجبيل لاستخدامه في إنتاج الميثانول واليوريا. وفي الإمارات، تقوم شركة بترول أبو ظبي الوطنية (أدنوك) باحتجاز 0.8 مليون طن سنويًا من ثاني أكسيد الكربون في مصنع الإمارات للحديد في أبو ظبي، وذلك ضمن المرحلة الأولى من مشروع التقاط الكربون واستخدامه وتخزينه، ومن المتوقع أن تحقق المرحلتين الثانية والثالثة احتجاز 5 ملايين طن سنويًا من غاز الكربون قبل عام 2030.

أنشأت سلطنة عُمان في إطار المبادرات المتعلقة بتقنية التقاط الكربون واستخدامه وتخزينه مشروع "الأفق الأزرق"، الذي يُنفذ بالتعاون بين شركة شل عُمان وشركة أكيو. يهدف المشروع إلى تعزيز جهود سلطنة عُمان في الحد من انبعاثات الكربون ودعم المبادرات البيئية المستدامة في المنطقة.

في الكويت، تم إطلاق عدة مبادرات متعلقة بتقنية التقاط الكربون واستخدامه وتخزينه. من أبرز هذه المشروعات ، المشروع الذي أنشأته شركة نفط الكويت، والمتعلق بالاستخلاص المعزز للنفط باستخدام ثاني أكسيد الكربون في حقل المناقيش غرب الكويت. هذا المشروع يهدف إلى زيادة عامل الاستخلاص بنسبة تصل إلى 10%. كما أطلقت شركة نفط الكويت مشروعًا مشتركًا مع كل من شركة البترول الوطنية الكويتية وشركة كيبيك، يهدف إلى التقاط أكثر من 100 طن متري من غاز ثاني أكسيد الكربون لاستخدامه على مدى 25 عامًا.

في البحرين، تم استكمال دراسة الجدوى الخاصة بمشروع احتجاز الكربون وتخزينه، الذي يهدف إلى تحقيق 10% من هدف خفض انبعاثات الكربون المحدد للدولة. هذا المشروع يمثل خطوة مهمة نحو تحقيق أهداف البحرين في تقليل انبعاثات الغازات الدفيئة والحد من تأثيراتها البيئية 2035.[23]

فيما يتعلق بأسواق الكربون، ما يزال الطلب والعرض على أرصدة الكربون في دول مجلس التعاون الخليجي في مراحله الأولى. فقد أبدت البحرين اهتمامًا بالتعامل مع آليات السوق والآليات غير السوقية للمشاركة في تعويض الانبعاثات. لتحقيق هذا الهدف، تسعى البحرين إلى إنشاء مخزون الكربون الأزرق في خليج توبلي وزراعة أشجار المانغروف. كما أطلق صندوق الثروة السيادية البحريني منصة "صفاء" الطوعية لتعويض انبعاثات الكربون، وهي مبادرة تهدف إلى تعزيز الجهود الوطنية في مجال مكافحة تغير المناخ.

وفي الكويت، دعم بيت التمويل الكويتي إنشاء أول منصة لتعويض الكربون، بهدف الحد من انبعاثات الكربون من خلال زيادة زراعة أشجار المانغروف وإطلاق مشاريع بيئية جديدة. أما سلطنة عُمان، فقد انتهت من إعداد المسودة النهائية لإطار السياسة العامة لأسواق الكربون، وذلك في إطار سعيها لتنظيم وتنشيط سوق الكربون ودعم الجهود البيئية المستدامة في البلاد.[24]

وسعت قطر إلى العمل كمنسق بين الجهات الفاعلة في الجنوب العالمي في سوق الكربون، حيث استضافت المجلس العالمي للبصمة الكربونية، الذي يُعد أول برنامج طوعي معتمد لتعويض انبعاثات الكربون في المنطقة. هذا البرنامج يعكس التزام قطر بتعزيز ممارسات الاستدامة البيئية والمشاركة الفاعلة في المبادرات العالمية لمكافحة تغير المناخ.

[23] Mari Luomi, Thomas Bosse, and Zlata Sergeeva. Lessons from Gulf Cooperation Council Countries' Participation in the Clean Development Mechanism (Riyadh, Saudi Arabia: King Abdullah Petroleum Studies and Research Center, 2023), Doi: 10.30573/KS–2023-DP04, page 25.

[24] Violet George, "Oman Finalizes General Policy Framework for Carbon Markets," *Carbon Herald*, August 30, 2024, https://carbonherald.com/oman-finalizes-general-policy-framework-for-carbon-marke.

وأنشأت المملكة العربية السعودية صندوق الاستثمارات العامة، وشركة مجموعة تداول السعودية القابضة شركة "الكربون الطوعية الإقليمية"، التي تُعرف اليوم بسوق الكربون الطوعية. وفي المزاد الطوعي الأول الذي نظمته شركة سوق الكربون الطوعية الإقليمية في تشرين الأول/أكتوبر 2022، تم بيع أرصدة تعادل 1.4 مليون طن من الكربون. كما نظمت الشركة مزادها الطوعي الثاني في نيروبي في تموز/يوليو 2023، حيث تم بيع أكثر من 2.2 مليون طن متري من الكربون، مما يعكس التزام المملكة بتطوير أسواق الكربون وتعزيز المبادرات البيئية المستدامة.

في عام 2021، أسست الإمارات العربية المتحدة سجلًا وطنيًا ونظامًا لتداول أرصدة الكربون، بالإضافة إلى بورصة وغرفة مقاصة لتداول أرصدة الكربون، والتي تم إنشاؤها بواسطة شركة "أبركاربون للتداول" ضمن سوق أبو ظبي العالمية. هذه المبادرة تهدف إلى تعزيز مشاركة الإمارات في أسواق الكربون العالمية وتسهيل تداول أرصدة الكربون لدعم الجهود الوطنية لتحقيق أهداف الاستدامة البيئية.

الخاتمة

يتضح من خلال دراسة موضوع تكنولوجيا التقاط الكربون واستخدامه وتخزينه كأحد الخيارات للحد من تغير المناخ، أنها تمثل خيارًا مجديًا وعمليًا وواعدًا في مكافحة تغير المناخ وتحقيق مستقبل منخفض الكربون. إلا أنها، رغم فوائدها، ليست الحل الأفضل أو الأسرع لتجنب كارثة الاحتباس الحراري، بل هي جزء من مجموعة من الحلول التي يجب أن تُعتمد بالتوازي مع إستراتيجيات أخرى لتحقيق الأهداف البيئية العالمية.

النتائج

1. تُعد تكنولوجيا التقاط الكربون واستخدامه وتخزينه من التقنيات الواعدة في مجال تقليص انبعاثات ثاني أكسيد الكربون.
2. يتم استخدام ثاني أكسيد الكربون الملتقط في العديد من التطبيقات الاقتصادية والطبية والغذائية، مثل الاستخلاص المعزز للنفط والغاز، وصناعة منتجات أخرى مثل الوقود السائل، بالإضافة إلى تصنيع سلع استهلاكية مثل البلاستيك . تقتضي تكنولوجيا التقاط الكربون واستخدامه وتخزينه تعاونًا بين عدة جهات، وتوفر مجموعة من الأطر التشريعية والاقتصادية والسياسية لضمان نجاحها.
3. تُعد تكنولوجيا التقاط الكربون واستخدامه وتخزينه ذات تكلفة عالية من حيث البنية التحتية، ما كان يشكل عائقًا أمام انتشار وتعميم هذه التكنولوجيا على نطاق واسع في العالم.
4. تبنت دول مجلس التعاون الخليجي إستراتيجية للحد من الانبعاثات الدفيئة، من خلال إنشاء عدة مشروعات خاصة بتكنولوجيا التقاط الكربون واستخدامه وتخزينه.

التوصيات

1. **تحديد دور التقاط الكربون وتخزينه في الاستجابة للإستراتيجيات والخطط المناخية الوطنية:**

يجب أن تساهم تقنيات التقاط الكربون وتخزينه بشكل فعّال في تحقيق الأهداف المناخية الوطنية وتقليل انبعاثات الغازات الدفيئة، مع تحديد دورها في تحقيق أهداف الاتفاقات البيئية الدولية . **وضع أطر تشريعية وتنظيمية لتكنولوجيا استخدام الكربون وتخزينه:** يجب أن تتوفر أطر حوكمة صارمة وتشريعات تنظيمية، مع إنشاء سجلات وطنية مرتبطة بسجل مركزي تابع للهيئة الإشرافية على أسواق الكربون بمنظمة الأمم المتحدة لضمان الشفافية والمساءلة.

2. **تطبيق معايير انبعاثات العادم الصارمة لوسائل النقل:**

من خلال فرض معايير صارمة على السيارات والشاحنات والحافلات، يمكن تقليل التلوث الهوائي وتحسين جودة الهواء، وهو ما يساعد في تعزيز فعالية جهود الحد من التغير المناخي.

3. **تشجيع الاستثمار في مشاريع التقاط ونقل وتخزين الكربون:**

يجب توفير المنح والقروض الميسرة، والإعفاءات الضريبية، وفرض سياسات تسعير الكربون التي تُدرج تكلفة الانبعاثات الكربونية في أسعار السلع والخدمات، مما يساهم في تحفيز الشركات والمستهلكين على اتخاذ قرارات بيئية أكثر استدامة.

4. **تعزيز التعاون الدولي والإقليمي:**

من خلال تبادل المعلومات وبناء القدرات وإقامة شراكات مع مختلف أصحاب المصلحة بما في ذلك الأفراد والمنظمات الحكومية والخاصة والمجتمعات المحلية، يمكن تحقيق تقدم سريع وفعال في مشروعات التقاط الكربون.

5. **دعم وتطوير البحوث في مجال التقاط الكربون:**

يتطلب الأمر تمويلًا كبيرًا للبحث والتطوير في مجال التقاط الكربون واستخدامه وتخزينه بهدف تحسين التكنولوجيا وجعلها أكثر كفاءة.

6. **خلق قيمة عالية طويلة الأجل لتخزين ثاني أكسيد الكربون:**

ينبغي تطوير إستراتيجيات تضمن أن تكون مشروعات تخزين ثاني أكسيد الكربون مستدامة وذات فائدة اقتصادية وبيئية على المدى الطويل.

7. **العمل على زيادة وعي وتثقيف المجتمع حول تكنولوجيا استخدام الكربون وتخزينه:**

يجب أن تتبنى الحكومات والمنظمات حملات توعية مستمرة لتعريف الجمهور بفوائد هذه التكنولوجيا وكيفية تأثيرها على مكافحة تغير المناخ.

8. **تخفيف إجراءات الحصول على التراخيص:**

تسهيل إجراءات الحصول على التراخيص لمشروعات استخدام وتخزين الكربون، يمكن أن يعزز من سرعة تنفيذ هذهالمشروعات .

9. **إنشاء وتعزيز أسواق الكربون:**

من خلال تعزيز التواصل مع أسواق الكربون العالمية كمشترٍ للأرصدة وفتح أسواق جديدة، يمكن زيادة فعالية هذه الأسواق ودعم الاقتصاد الكربوني العالمي.

10. **إنشاء أنظمة رصد وتحقيق صارمة:**

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Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Data Availability

No data was used for the research described in the article.

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The effects of alkaline pre-treatment on the combustion profiles of fuel briquettes produced from mango seed shells compared to untreated ones

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ABSTRACT

The need for an alternative energy source to complement the use of fossil fuels and mitigate the environmental and economic challenges arising from the overexploitation of nonrenewable energy sources has led to the use of biomass briquettes as a suitable alternative. This study investigates the performance of alkaline-pretreated biomass briquettes produced from mango seed shells. The pulverized sample was divided into two equal samples. A portion of the sample was soaked in 0.3 M sodium hydroxide for 3 hours, then washed and dried. The second portion remained untreated. Eighty grams of both the treated and untreated samples were thoroughly blended with 20g of starch slurry and fed into the briquetting machine, where they were compressed to produce briquettes. The produced briquettes were sun-dried for 4 weeks and then analyzed. The proximate composition, physical properties, combustibility properties, and SEM of the briquettes were determined. The alkaline-treated sample (BTS) had a value of 1498.67 ± 1.04 kJ/kg, and the untreated sample (UTS) had a value of 1495.44 ± 1.72 kJ/kg. The compressive strength of alkaline pretreated (BTS) was 0.783± 0.250. It took 20 minutes for the treated sample to boil one litre of water, while it took 22 minutes for the untreated sample to boil the same volume. The results showed that both treated and untreated samples could be used for briquette production; however, the treated briquette sample had better performance and hence was a better fuel.

Keywords: Briquette, Proximate Compression, Combustibility**.**

1. Introduction

It is evident that the world is running short of its energy supply generated from fossil fuels and wood, which is due to the rapid depletion of these non-renewable energy reserves. However, exploring an alternative to this hydrocarbon-based energy has become a matter of economic and environmental importance. Expanding energy services, especially to the rural households, while simultaneously addressing the health and environmental consequences has become a matter of concern (Qi et al., 2023). According to Adeoye & Lawal (2025), energy demand from fuelwood is expected to increase to 91 million tonnes by 2030, resulting in a continued deforestation rate. This highlights the need to explore affordable energy systems for domestic and industrial use in the country, with a focus on renewable, eco-friendly, and cost-effective sources. Fossil fuels, which are non-renewable energy sources, also pose a potential threat to the climate due to the high emission of greenhouse gases (CO_2, CH_4, NO_2,etc.). Considering all these factors has become a central stimulant for research on renewable energy sources.

Recently, there has been a growing global interest in developing technologies that harness renewable energy sources. Also known as green energy, it is utilized for both environmental and economic reasons (Obi et al., 2022; Udume et al., 2022). Biomass is naturally abundant and presents a renewable energy opportunity that could serve as an alternative to fossil fuels. Nigeria has approximately 71.9 million hectares of arable land, and various grasses are cultivated for primary agricultural purposes. The enormous forest resources and landmass in Nigeria, with flourishing vegetation, imply that the regeneration of these resources through appropriate means can be a simple way of contributing to solving a seemingly intractable power supply problem (Ferronato et al., 2022). It is common in most Nigerian rural communities to fell trees. The problem of felling trees for use as a fuelwood source hurts the environment. One way to limit deforestation and protect the environment is through the briquetting of flammable materials. Therefore, using biomass, which is organic waste from this vegetation, will tremendously reduce deforestation and provide an alternative renewable energy source. The effective utilisation of these materials offers many advantages, one of which is their role as a renewable and sustainable energy feedstock for the production of solid fuel briquettes (Zhang et al., 2018). Briquettes are flammable materials formed by the compression or densification of matter into solid form to be used as fuel. Briquetting is a process of binding together pulverized carbonaceous matter, often with the aid of a binder (Obi et al., 2022). The common forms of briquettes are coal briquettes and biomass briquettes. Discovery has shown that binder type and curing conditions exert the greatest influence on briquette quality (Udume et al., 2022). Therefore, it is necessary to carry out studies on different treatment methods and identify the most suitable ones for maximum combustion output. Hence, this research tends to study the effects of alkaline pre-treatment on the combustion profiles of fuel briquettes produced from mango seed shells against the untreated one.

2. MATERIAL and METHOD

2. 1. Materials

The mango shell of *Foetide lour* (Julie), a small-seeded species, was collected within Aliero Local Government because of its low moisture content of 72.04%, compared to other varieties of mangoes in the region. Starch was used as a binder. All necessary glassware was pre-treated by soaking in a dilute nitric acid solution for 24 hours, followed by thorough rinsing with distilled water prior to use. The chemicals, reagents, and solvents employed throughout the study were of analytical grade and general-purpose quality.

2. 2. Sample Pre-treatment

The collected sample was dried in direct sunlight for 2-3 days to reduce its moisture content before being pulverised into powder form using a mortar and pestle and a mechanical grinding engine. The powder was sieved through a 60-mesh sieve to achieve the required texture size and to remove impurities. The prepared sample was divided into two equal portions.

2. 3. Alkalization of the Sample

The first portion of the sample was soaked in an alkaline solution of NaOH with an optimised concentration of 0.3M. The equivalent in weight of NaOH was soaked with the mango shell powder at a ratio of 3:1 for three hours at room temperature (Bamisaye & Rapheal, 2023). The pre-treatment helps to reduce the lignin content in the mango shell, making it easier to bind its particles together. The other portion was left untreated.

2. 4. Briquettes Production

80g of the sieved alkaline-treated sample and untreated sample were independently mixed with 20g starch binder in the ratio of 4:1 (Obi et al., 2023). The briquettes were produced using a locally made briquetting machine; the mixture was poured into the cylindrical metal container of the briquetting machine and covered with an iron desk with the combined effect of the compression.

Figure 1. Image of homemade fabricated briquetting machine and produced briquette

2. 5. Proximate Analysis

A proximate analysis was conducted on the produced briquettes.

1. Percentage Moisture Content (PMC).
2. Percentage Ash Content (PAC).
3. Percentage Fixed Carbon (PFC).

2. 6. Determination of Briquette Physical Properties

The compressive strength of the briquettes was evaluated following the procedure outlined by Yakubu & Sadiq (2021). The dimensions length and width of each briquette were measured and recorded prior to testing. Each sample was centrally positioned on the lower plate of the testing machine. The plate was then raised electrically until it made contact with the upper plate, and the strain dial gauge was reset to zero. Initial readings for both the strain dial and the load dial at zero compressive force were recorded. A stopwatch was used to time the measurements, with load dial readings taken at every 0.2 mm of displacement, and corresponding strain dial readings noted as well. Additional readings were recorded at 0.4 mm intervals. The loading process continued until a clear indication of failure was observed evidenced by a drop or no change in load across several consecutive

readings. Once failure was confirmed, the machine was halted, the motor allowed to come to a complete stop, and the setup reversed before the load was removed. The briquette sample was placed on the movable bed, and the control lever was operated upward to establish contact between the fixed upper plate and the movable lower plate. As soon as a crack appeared in the briquette, indicating compression failure, the dial reading was noted, and the corresponding force value from the strain dial was recorded.

The compressive strength was then calculated using Equation (1), and the result was expressed in kilonewtons per square meter (kN/m²).

$$\text{Compressive strength} = \sigma = RC_R (100 - \varepsilon\%) / 100A_0 \times 1000 \quad (1)$$

Where:

R: dial reading, C_R: calibration load dial reading (2.11 Div.) constant, A_0 is cross-sectional area = $\pi D^2/4$, D: diameter of briquette (mm), Ɛ is the strain of sample: σ, Ɛ%: DL/L_0, DL is change in length of sample at compression, and L_0 is initial length of sample before compression.

The density of the briquettes was determined using the formula below:

$$Density = \frac{\text{weight of briquette(g)}}{\text{volume of briquette}(cm^3)} \quad (2)$$

2. 7. Combustion Analysis

The following combustion analysis was carried out.

1. Calorific Value Determination.
2. Ignition Time Determination.
3. Determination of Burning Rate.
4. Combustibility Test.

2. 8. Lignocellulose Composition Analysis

Analysis of lignin and cellulose was carried out by using the method adopted by Zhang & Zhou (2024), where a mixture of 1 g of dried sample of mango shell and 150 mL of aquadest was heated in a water bath at a temperature of 90 - 100°C for 1 h. The mixture was filtered, and the residue was washed with hot water (300 mL). The residue was oven-dried until a constant weight was achieved (b). It was then combined with 150 mL of 1 N sulphuric acid (H_2SO_4) and heated in a water bath at 90–100 °C for one hour. After heating, the mixture was filtered, and the remaining solid was rinsed thoroughly with 300 mL of distilled water (aquadest), followed by drying (c). The dried material was then soaked in 10 mL of 72% H_2SO_4 at room temperature for 4 hours. Subsequently, 150 mL of 1 N H_2SO_4 was added, and the mixture was subjected to reflux in a water bath for one hour. The resulting solid was washed with 400 mL of distilled water, then dried in an oven at 105 °C and weighed until a stable mass was reached (d). Finally, the residue was incinerated to ash and weighed again (e). The percentages of cellulose and lignin were then determined using the following calculations:

$$\% \text{ cellulose} = \frac{c-d}{a} \text{ X } 100\% \quad (3)$$

$$\% \text{ lignin} = \frac{d-e}{a} \text{ X } 100\% \quad (4)$$

.

Where:

a: sample weight (g), c : the residue weight (g) at the third weighing, d : the residue weight (g) at the fourth weighing, e : the weight of ash (g).

2. 9. Statistical Analysis

The average value of all the parameters analysed would be computed using arithmetic mean and one-way analysis of variance (ANOVA) to determine the probability that two populations are the same and to know whether there is a significant difference.

3. Result and discussion

3. 1. Proximate Compositions of the Briquette Sample

The results of the proximate analyses of briquettes are shown in **Table 1**. It was observed that the moisture content of the untreated sample was about 6.5%, while that of the alkaline-treated sample was 4%. The moisture content of the untreated sample was more than that of the alkaline, which implies that the treatment decreases moisture content. Higher moisture content value is reported to have negative effects on the combustion characteristics of briquettes (Demirbaş & Şahin, 1998). Since higher moisture content indicates a greater degree of wetness in the briquettes (Obi et al., 2023), low moisture content is required to protect against decomposition and disintegration of briquettes during storage and handling.

Ash content for the untreated sample was 1.83%, while that of the alkaline-treated sample was 2.5%, which is not above the maximum required value of not greater than 20% (Abimbola et al., 2022). This revealed that treatment increases ash content. These results compared favourably to the good-quality charcoal range (1.2% to 8.9%) as stated by Abayomi et al (2022) (Bamisaye et al., 2024). The work agreed with the work of Zhang et al., 2023, who recorded 2.5% of ash content for shea nut shell (Qi et al., 2023).

Also, the volatile matter of the two samples is 79.00% to 85.33% for the alkaline-treated and untreated samples, respectively. The fixed carbon content result for the untreated sample was 6.33% and 14.17% for alkaline treatment; hence, treatment increases the fixed carbon content. Generally, the higher the volatile matter, the better the briquettes (Adesola Ajagbe et al., 2025) since high volatile matter briquettes ignite easily. The fixed carbon is used to determine the heating value and acts as a heat generator during combustion (Ferronato et al., 2022). The higher the fixed carbon content of a briquette, the greater the calorific value.

Table 1. Result of the Proximate Analysis of the Briquette

	Untreated Sample	Alkaline-treated sample
Moisture (%)	6.50 ± 0.50	4.33 ± 1.04
Ash (%)	1.83 ± 0.29	2.50 ± 0.50
Volatile matter (%)	85.33 ± 1.15	79.00 ± 0.00
Fixed carbon (%)	6.33 ± 1.04	14.17 ± 1.44

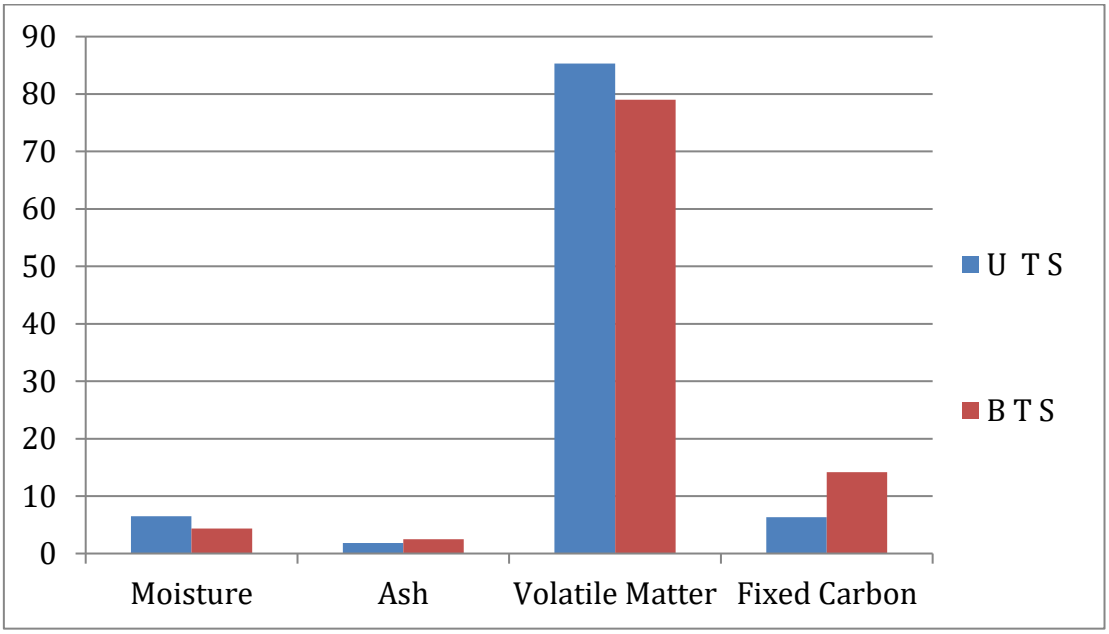

Figure 2. Proximate Analysis

3. 2. Physical Properties of the Briquette

Table 2 shows the result of the physical properties of the respective briquette samples, results of the physical properties of the briquettes are shown in Table 2, which shows that the alkaline sample has the highest density and compressive strength. The compressive strength from the untreated sample was 0.717 ± 0.012 N/mm^2 while that of the alkaline-treated sample was 0.783 ± 0.250 N/mm^2. It was observed that there is no significant difference in the compressive strength of the respective samples with ($p<0.05$) on this property. This is probably because they were compressed at a constant force upon the same cross-sectional area of the briquettes. The compressive strength values indicate that the briquettes are suitable for transportation, packing, and storage. The high compressive strength of the alkaline-treated sample, as shown in Table 2, could be attributed to the loss of hemicellulose in the samples. According to Oyibo et al 2020, NaOH-treated samples usually have a decreased fibre diameter of the samples' particles because of the loss of hemicellulose in the samples.

The density of the briquettes decides how long they would burn and the amount of fly ash they would release while burning High-quality briquettes should have high-energy content and burn for a longer time. The density of the briquettes for the untreated sample was 0.359 ± 0.005 g/cm^3, while that of the alkaline sample was 0.357 ± 0.00 g/cm^3. Thus, there was a significant difference in the density of the briquettes at ($p<0.05$). The briquette densities were found to be lower than that of the mahogany tree, which was 0.682 g/cm^3 as stated by Zhang & Zhou (2024).

Table 2. Physical Properties

	Compressive Strength (N/mm^2)	**Density (g/cm^3)**
Untreated sample	0.717 ± 0.012	0.359 ± 0.005
Alkaline-treated sample	0.783 ± 0.250	0.359 ± 0.005

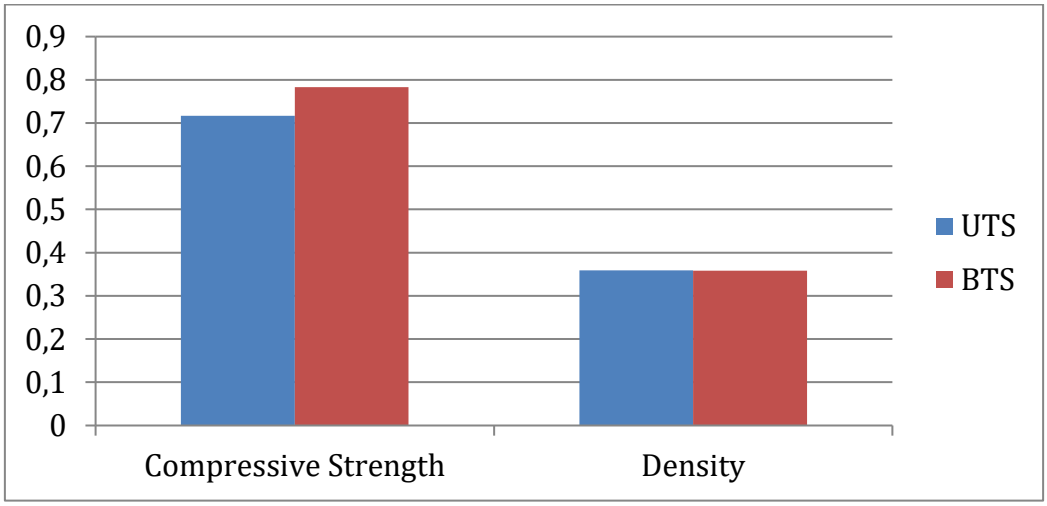

Figure 3. Physical Properties of Briquette Sample

3. 3. Combustibility Test of the Briquettes

Table 3. Combustion Characteristics

	Calorific value (KJ/Kg)	Burning Rate (g/min)	Ignition Time (mm/s)
Untreated Sample	1495.44 ± 1.72	28.547 ± 0.011	45.550 ± 0.580
Alkaline-treated sample	I498.67 ± 1.04	18.690 ± 0.012	41.540 ± 0.528

Table 3 shows the result of the combustion properties of the respective briquette samples. The results show that the calorific value of the treated sample, as shown in **Table 3**, was higher than the calorific value of the untreated sample. This shows that there is a significant difference in the calorific value when a biomass is treated. This is probably due to the fact that treatment of a sample affects its moisture content. The calorific values obtained range between 1495 KJ/Kg and 1498 KJ/Kg. The higher the calorific value, the better the combustion characteristics for energy generation.

The untreated sample had the highest burning rate, even though it had the lowest calorific value. However, this deviation was explained by the SEM result in **Figure 4**. The untreated sample has a very porous interface; the higher the porosity, the higher the circulation of oxygen, which increases the combustion rate (Ngene et al., 2024). A slow burning rate is desirable because less heat is required for cooking (Yunusa et al., 2023). The result of the burning rate, as presented in **Figure 4**, agrees with the results of Zhang et al., 2023**,** who treated carbonised rice husk with different binders.

The time taken for the untreated sample to attain a steady glow was higher than the time taken for the treated sample to attain a steady glow, as shown in **Figure 4**. The ignition time of both treated and untreated samples is lower than that of Abayomi et al, 2022 (Bamisaye et al., 2024).

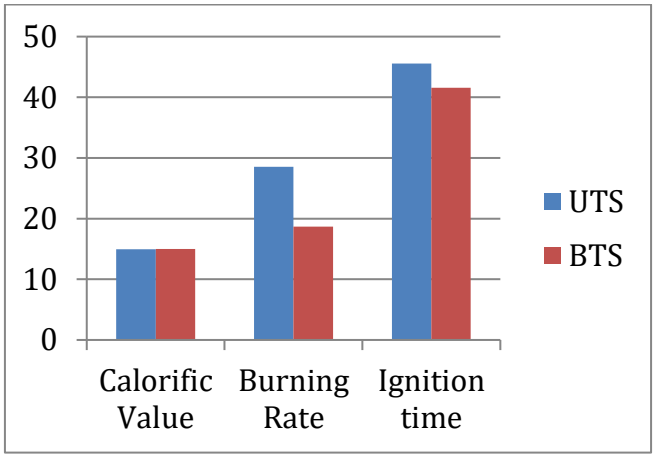

Figure 4. Combustion Properties of Briquettes Sample

3. 4. Combustibility Test

Figure 5 below shows the result for the water boiling test on the alkaline-treated sample and the untreated sample.

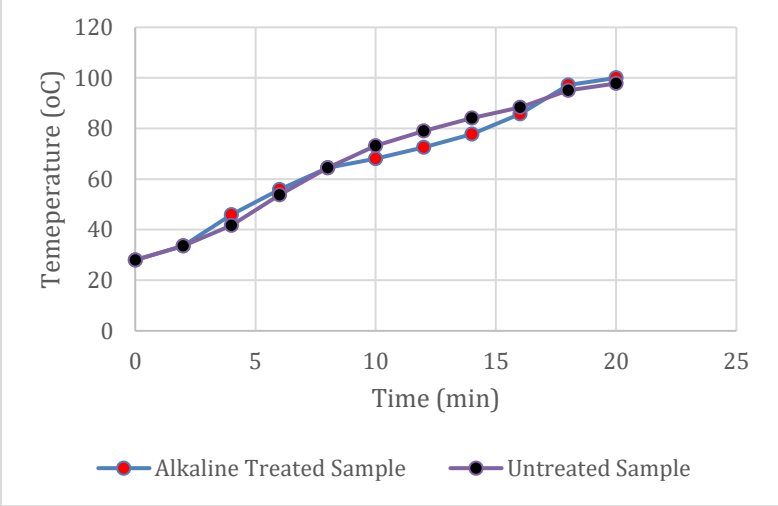

Figure 5. Water Boiling Test

The results from the combustibility test show that the alkaline-treated sample has a higher boiling rate at a lower temperature range between 0^0C to 5^0C, and a lower rate between 5^0C to 10^0C. Generally, the alkaline-treated briquette has a shorter combustibility time of 20 minutes than the untreated sample, which has a combustibility time of 22 minutes. These results show that the treated sample boils water faster than the untreated sample.

3. 5. Morphology of the Produced Briquette

The surface morphology of the alkaline-treated sample and the untreated sample are shown by scanning electron microscopy in Figures 6 and 7, respectively.

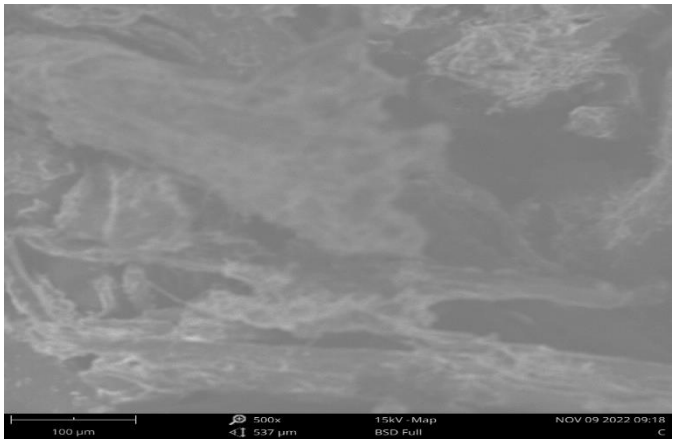

Figure 6. Morphology of Alkaline-Treated Sample at 1500x Magnification

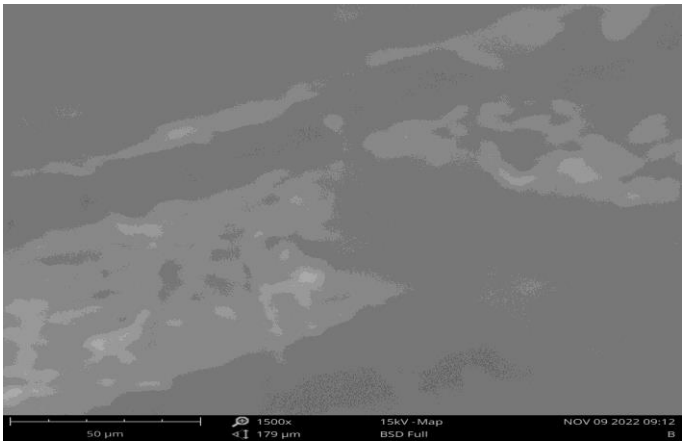

Figure 7. Morphology of Untreated Sample at 1500x Magnification

From the results, it can be observed that the outer surface texture of the untreated sample was porous, and there was an absence of destructive features on the surface. The alkaline pre-treatment caused more compaction of the briquette material, as shown in **Figure 6**. This compaction was due to the pressure of hemicellulose, lignin, and other impurities such as wax, pectin, and grease covering the components and protecting the cellulose inside (Zhang et al., 2018). The destructive degree of roughness of the NaOH-treated samples was attributed to the penetration of the NaOH solution into the samples. NaOH breaks down and removes hydroxyl groups and surface impurities in the amorphous non-cellulose constituents, which increases the number of crystalline sites exposed on the fibre surface (Zhang et al., 2018).

4. Conclusion

This research investigated and compared the combustion characteristics of mango seed shell briquettes in both treated and untreated forms. Experimental results indicated that briquettes derived from both sample types are suitable as biomass fuel sources. Nonetheless, the treated briquettes exhibited superior biofuel properties compared to their untreated counterparts. Specifically, the treated samples demonstrated an enhanced calorific value, higher density and compressive strength, greater fixed carbon content, reduced moisture levels, and required less time to boil an equivalent volume of water under identical conditions. Scanning Electron Microscopy (SEM) revealed that treatment with sodium hydroxide (NaOH) altered the surface structure, making it rougher due to the removal of amorphous, non-cellulosic components as the solution infiltrated the fibre

surfaces. This increased surface roughness improved fibre-matrix interfacial bonding, thereby enhancing resistance to moisture, as reflected in the lower moisture content of the treated briquettes.

5. Recommendations

Based on the findings of this study and the conclusion made, it is recommended that:

1. More research should be focused on briquettes using varied feedstocks (biomass).
2. Reagents other than NaOH should be explored as alkalis in the treatment of biomass for briquette production.
3. Acid-treated mango seed briquettes should be researched.

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Data Availability

No data was used for the research described in the article.

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Improving Grayscale Medical Images (X-Rays, MRI, CT Scans)

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ABSTRACT

Medical images provide critical information that physicians need to diagnose a condition and make appropriate treatment decisions. The diagnostic process relies heavily on human perception. Unfortunately, the potential for perceptual errors is unacceptable, impacting patients' lives. Therefore, image enhancement represents a crucial step in supporting medical diagnosis by improving its quality. In this research, we applied a new algorithm to enhance X-ray, MRI, and CT images. This algorithm aims to improve contrast and sharpness based on an empirical equation using trigonometric functions (cos) based on Fourier transforms and changing the value of one of its main parameters. Nasal polyps were more clearly identified in X-rays, and brain tumours were more clearly identified in MRI and CT scans. Histograms were used before and after enhancement, and we observed a significant difference between the original and enhanced images in terms of the histogram shift toward unity, demonstrating the success of this algorithm in improving contrast and organ prominence.

Keywords: X-rays, MRI, CT scans, Medical images, Improve medical images, Medical image Enhancement.

1. Introduction

Image enhancement is a fundamental stage of image processing. This enhancement is often used to improve image quality by highlighting specific information and removing unnecessary details based on user requirements. Image enhancement has two functions: increasing visual impact and facilitating computer processing. Image enhancement offers numerous advantages, including noise reduction, edge sharpening, brightness enhancement, and contrast enhancement (Al-Khafaji & Sahib, 2024; Hussain et al., 2022). Medical images are often produced with low contrast, low intensity, noise, and distortion due to limitations in medical equipment. Due to their low quality, these images cannot be used for diagnosis. Therefore, to create high-quality images with more information that facilitate better analysis, careful image processing is necessary (Pourasad & Cavallaro, 2021). Medical imaging is a rapidly expanding area of study that is used to identify and treat diseases early. Image processing is becoming increasingly important in the healthcare sector. Medical imaging is a group of technologies that visualise the human body to diagnose, track, or treat medical disorders. It includes technologies such as endoscopy, computed tomography (CT), positron emission tomography (PET), magnetic resonance imaging (MRI), ultrasound, X-rays, and others. To assist physicians worldwide in diagnosis, treatment, and prevention, medical imaging is essential (Agrawal et al., 2025; Li et al., 2019; Pinto-Coelho, 2023). In this paper, a novel algorithm based on empirical equations and trigonometric functions is proposed for medical image enhancement, and it is applied to X-ray, MRI, and CT images.

2. Medical Images

Many medical imaging techniques have been employed to examine anatomical features, including muscles, bones, blood vessels, tissue types, and diseased areas such as cancer (Kumari, 2025; Rehman & Mir, 2025; Sule & Ampofo, 2025). Therefore, this work focuses primarily on the importance of improving medical images for accurate analysis and diagnosis. This section will cover three medical imaging methods: magnetic resonance imaging (MRI), computed tomography (CT), and X-rays.

2. 1. X-Ray Images

X-rays are used to image the internal structure of the human body and are among the most commonly used diagnostic tools in the medical field. They help radiologists identify internal issues by providing images of the body's internal anatomy. It is the most practical imaging technique for detecting bone fractures. Despite its many benefits, X-ray technology produces images with little contrast. The amount of liquid in the human body is the primary cause of the low contrast of X-ray images. Increasing the X-ray's capacity to take images could damage a person's body or bones (Akbar et al., 2025; Fan et al., 2025; Ou et al., 2021).

2. 2. Magnetic Resonance Images (MRI)

The medical imaging technique known as magnetic resonance imaging (MRI) is founded on the same ideas as spectroscopy using nuclear magnetic resonance. The most effective and noninvasive method for clinical illness diagnosis is magnetic resonance imaging (MRI) (Chen et al., 2023; Reda et al., 2021). The MRI scanner creates images of the body's tissues, organs, and other structures using magnetic and radio waves. It produces images that are superior at portraying fine details. As a result, an MRI scanner may be used to image every tissue in the body. Bones and other tissue with the fewest hydrogen atoms seem dark, but fatty tissue with abundant hydrogen atoms appears considerably brighter. By altering the timing of the radio wave pulses, information regarding the various tissue types that are present can be obtained (Gómez-Guzmán et al., 2023; Nayak et al., 2022).

2. 3. Computed Tomography Images (CT)

CT is a diagnostic technology that combines X-ray equipment with a computer and a cathode ray tube display to produce images of cross sections of the human body. Each profile is reconstructed by the computer into a 2D image of the slice that was scanned. 3D CT can be obtained using spiral CT (Dremel et al., 2025; Falgout et al., 2024; Stewart et al., 2025).

3. Literature Survey

Pourasad and Cavallaro enhanced compressed image quality in 2021 by employing a variety of optimization strategies. They researched various approaches and offered a number of comparison findings. Ultimately, performance measurements were retrieved and examined using cutting-edge techniques. PSNR, MSE, and SSIM were the three performance measures they employed for medical image samples. These measurements perform better than other image processing methods, according to a thorough analysis (Pourasad & Cavallaro, 2021). In 2022, Idowu et al. introduced an enhanced image enhancement method for medical image processing. This method uses three distinct enhancing strategies. The first technique is Unsharp Masking (USM). A Logarithm Transform (LT) receives the output of the USM processing, and the LT output is then fed into an AHE. AMBE, PSNR, Entropy, and Predicted Opinion Score were used to assess the effectiveness of the suggested approach. A reliable result for AMBE and PSNR Entropy was obtained using the suggested approach (Idowu et al., 2022). In 2023, Mouzai et al. suggested an Xray-Net method to improve low-contrast photos using a self-supervised pixel contrast expansion. The approach consists of three primary steps: (1) preprocessing, which includes calculating the average brightness to create an X-ray contrast-based classification; (2) creating a traditional neural network model; and (3) adaptive contrast expansion. When compared to other state-of-the-art techniques, Xray-Net's results show greater performance in low-contrast enhancement (Mouzai et al., 2023). Anitha et al. (2024) improved image quality by removing uniform, Gaussian, and salt-and-pepper noise using various filtering and contrast enhancement approaches (Anitha et al., 2024). In 2024, Babu and Venkatanarayana presented a novel approach to multimodal image fusion for medical imaging (MRI, CT) that utilizes low- and high-frequency weights derived from the CSGWO algorithm. The suggested approach uses quadrupole wavelet transform (QWT) to extract low- and high-frequency components, contrast enhancement in preprocessed images, and cartoon texture (CT)-based analysis. The fusion quality index and other objective criteria were used to assess the suggested approach. The outcomes showed how the suggested approach outperformed alternative approaches and how well it worked to raise the general calibre of medical photographs (Babu & Venkatanarayana, 2024). To regulate the total contrast augmentation, Singh and Raj (2024) suggested a histogram cropping technique based on eight-degree polynomials. Through the use of a single objective fitness function, the technique also establishes an exposure threshold value and a genetic algorithm (GA) to improve the histogram segmentations, guaranteeing constant brightness and reducing information loss. A number of metrics were employed, including the Feature Similarity Index Method (FSIM), Entropy, and PSNR (Yadav & Donvir, 2025). A new AI-powered approach for automatically creating tactile and three-dimensional medical X-ray images was proposed by Yadav and Donvir in 2025. The system generates high-resolution depth maps suitable for tactile display by utilising image processing techniques such as depth estimation and image enhancement. Accuracy and processing time are objective criteria used to assess system performance. This study shows that an automated method to increase access to medical imaging is feasible, which could improve diagnostic precision and advance healthcare inclusivity (Yadav & Donvir, 2025).

4. Mathematical Analysis

We will apply an empirical equation using trigonometric (cosine) transformations because they are the basis for the frequency representation in the Fourier transform, which is used to remove noise and enhance edges on medical images under study (X-rays, MRIs, and CT scans). To improve image quality: -

$$I_E(x,y)=\begin{bmatrix}|\cos(2\pi f I_o(x,y))|\\|\cos(2\pi f I_o(x,y))|\\|\cos(2\pi f I_o(x,y))|\end{bmatrix} \dots\dots\dots(1)$$

Where:

$I_E: (x, y)$ is the Enhancing image.
$\mathcal{F}$: is the Frequency coefficient.
$I_O: is\ the\ Original\ image.$

5. Image Acquisition

This work was carried out in MATLAB R2021a. The medical images used for testing are X-rays, MRIs, and CT scans. An X-ray was taken from Sama Clinic in Abu Sakhir District in Najaf Governorate for a patient suffering from nasal polyps. An MRI and CT scan were taken from the German Hospital for the same patient suffering from a brain disease.

6. MATLAB Algorithm Flowchart

Figure 1. illustrates the fundamental algorithm stage:

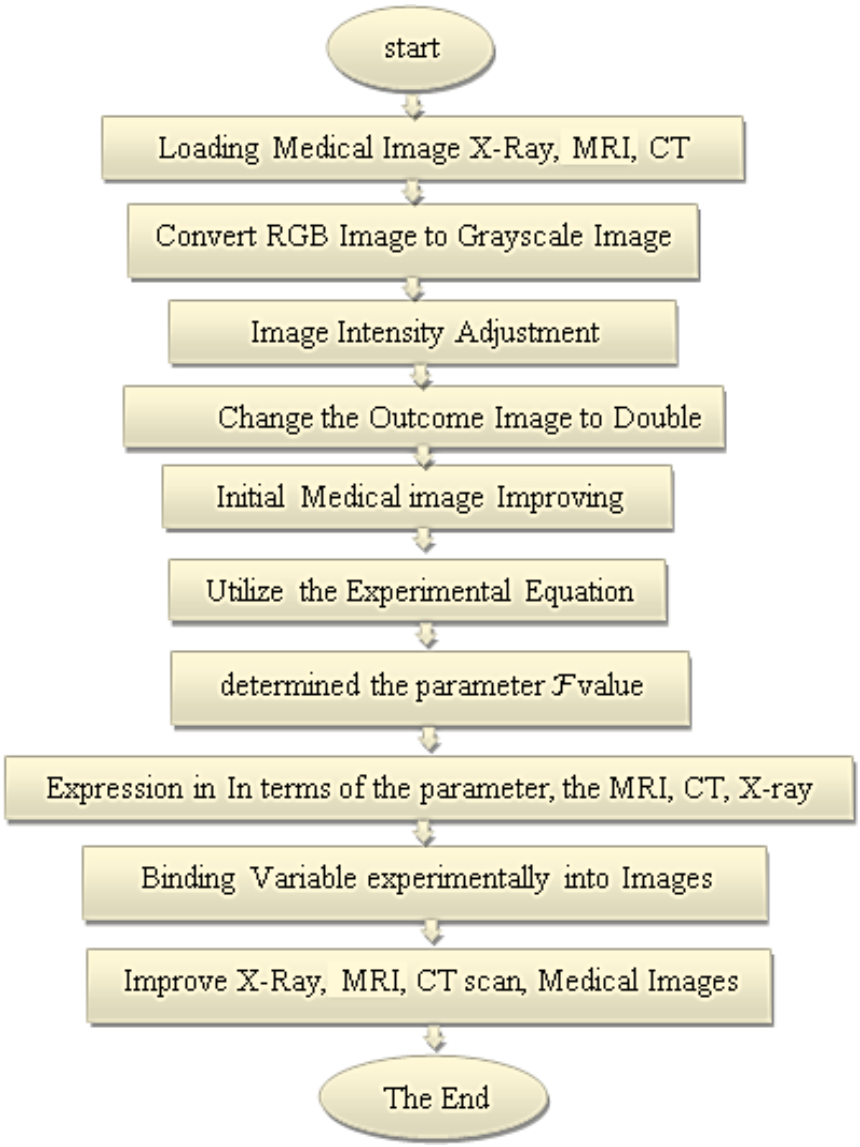


Figure 1. flowchart of propose algorithm

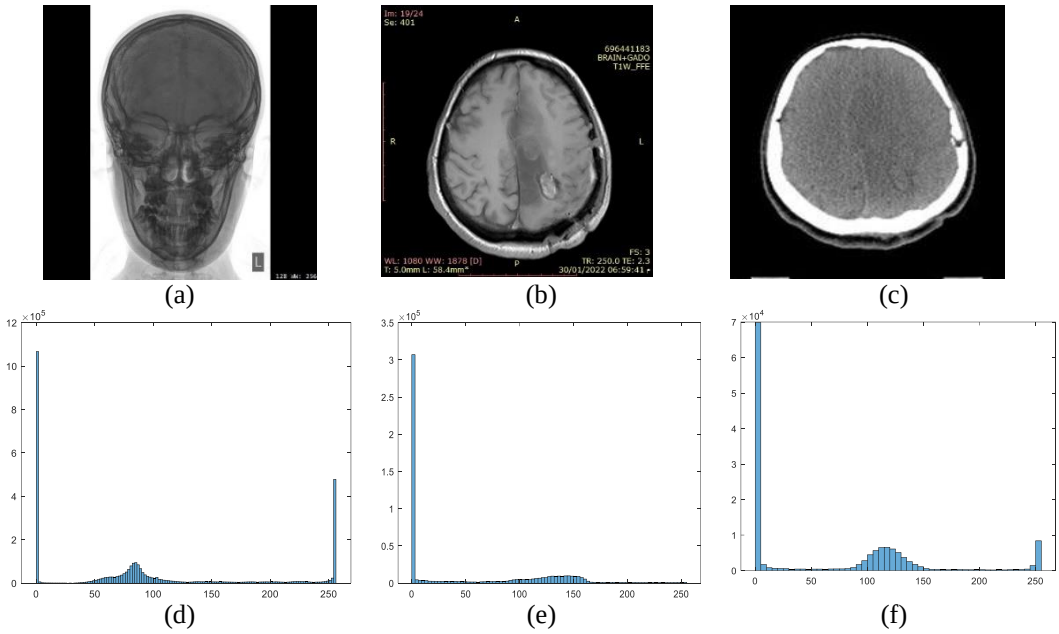
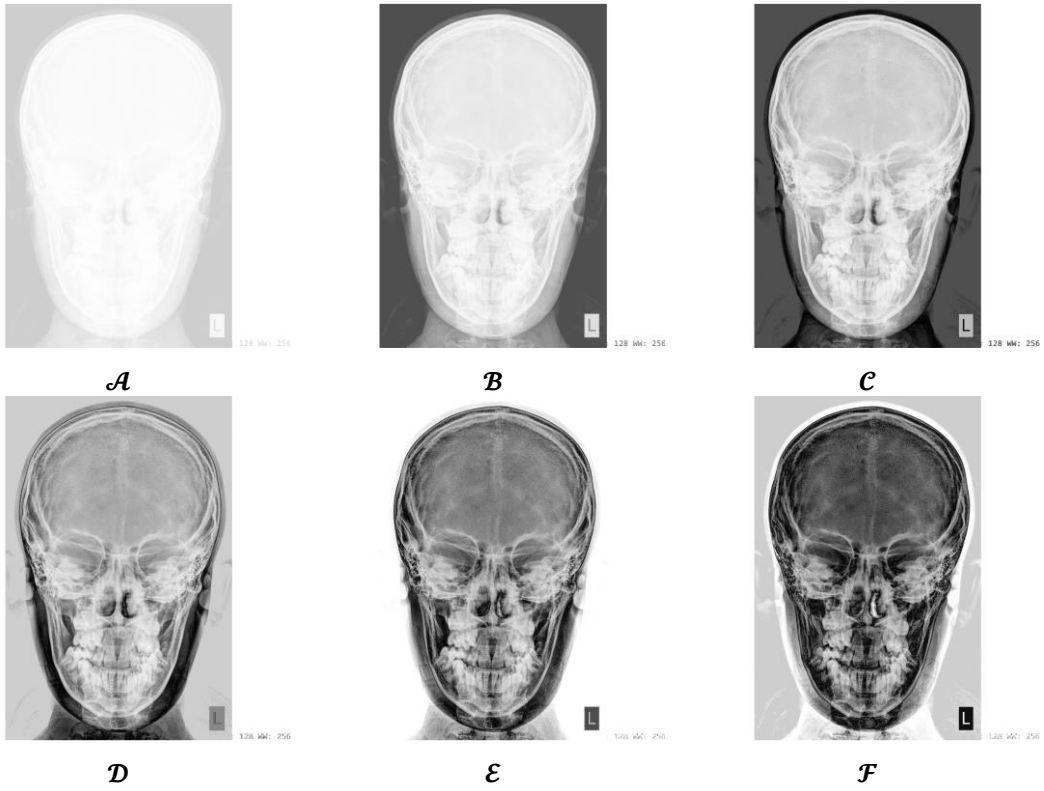


Figure 2. An original X-ray image, (b) An original MRI image (c) An original CT scan image(d) the related histogram of image in (a),(e) the related histogram of image in (b),(f) the related histogram of image in (c)

7. Method Adopted and Experimental Outcomes



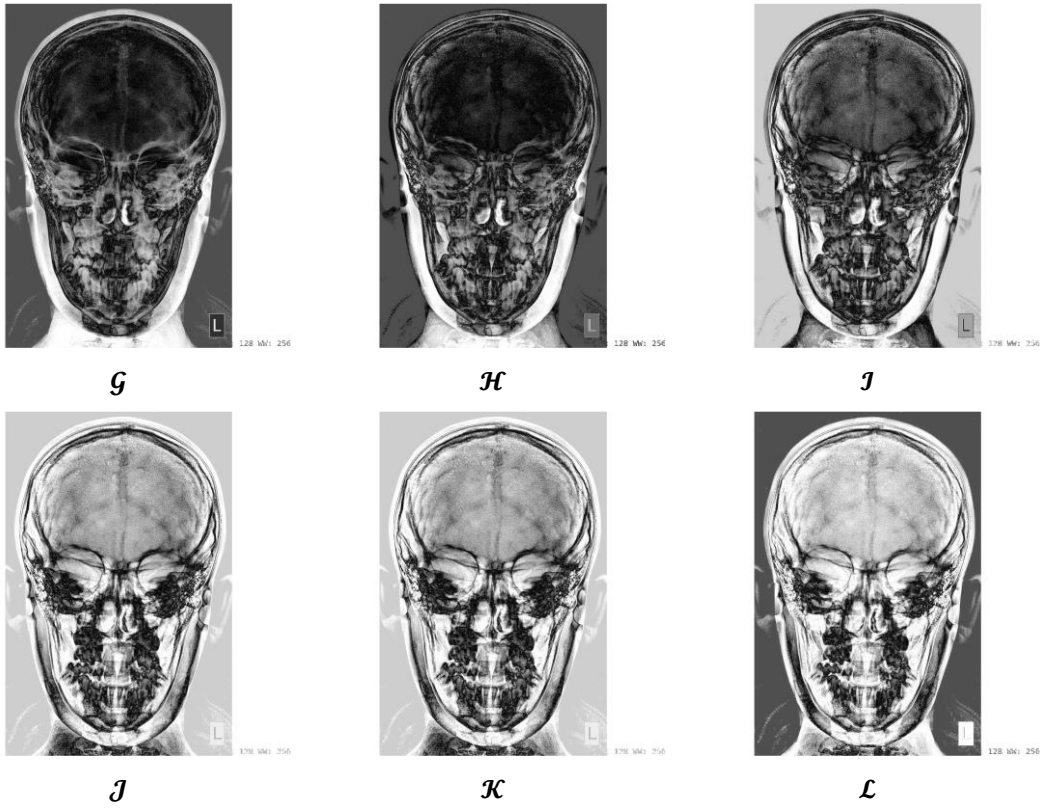
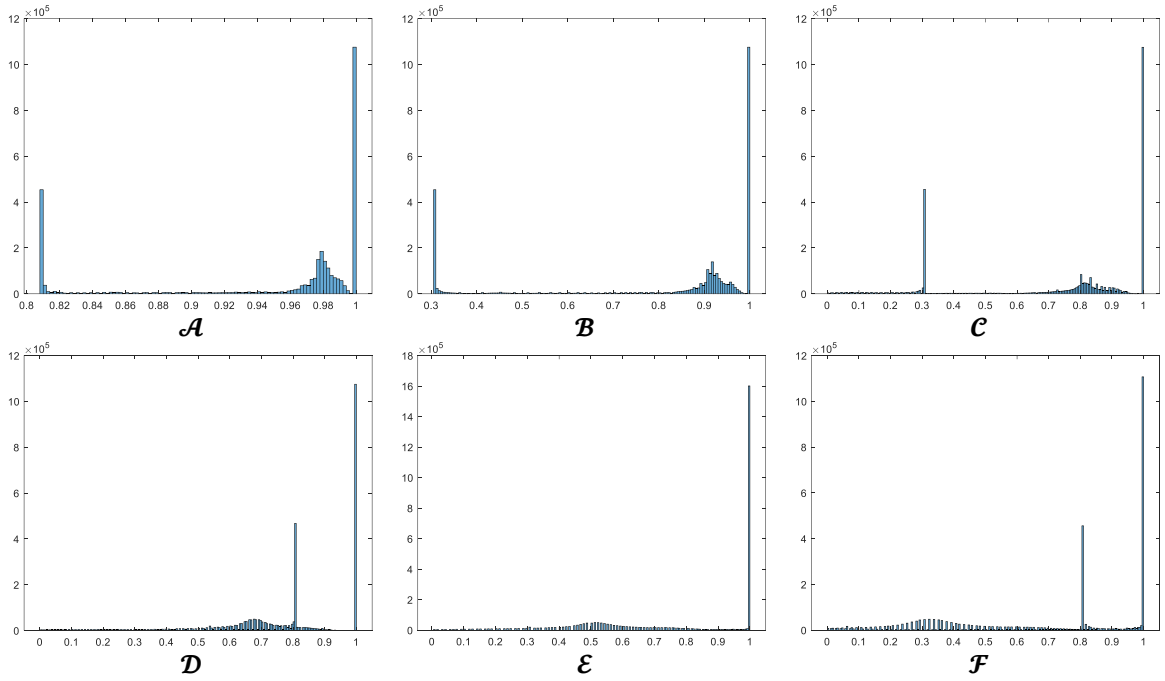


Figure 3. The resulting X-ray images ($\mathcal{A}$) resulting image when $\mathcal{F}$ =0.1 ($\mathcal{B}$) resulting image when $\mathcal{F}$ =0.2 ($\mathcal{C}$) resulting image when $\mathcal{F}$ =0.3 ($\mathcal{D}$) resulting image when $\mathcal{F}$ =0.4 ($\mathcal{E}$) resulting image when $\mathcal{F}$ =0.5 ($\mathcal{F}$) resulting image when $\mathcal{F}$ =0.6 ($\mathcal{G}$) resulting image when $\mathcal{F}$ =0.7 ($\mathcal{H}$) resulting image when $\mathcal{F}$ =0.8 ($\mathcal{I}$) resulting image when $\mathcal{F}$ =0.9 ($\mathcal{J}$) resulting image when $\mathcal{F}$ =1.1 ($\mathcal{K}$) resulting image when $\mathcal{F}$ =1.2($\mathcal{L}$) resulting image when $\mathcal{F}$ =0.9



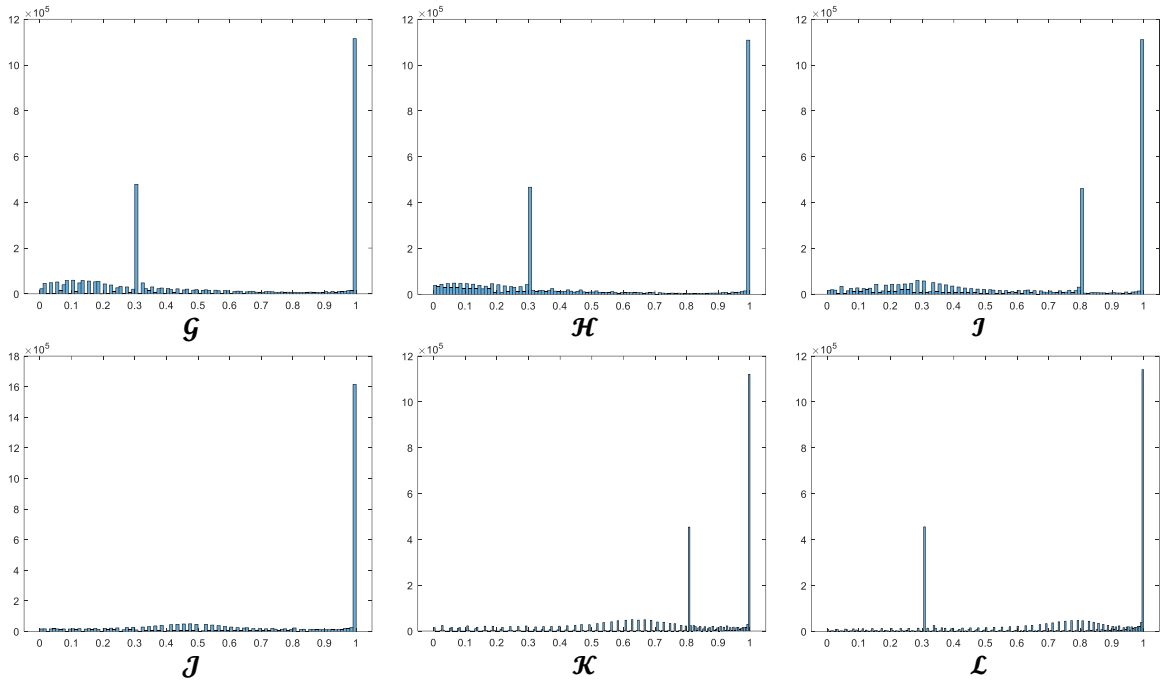
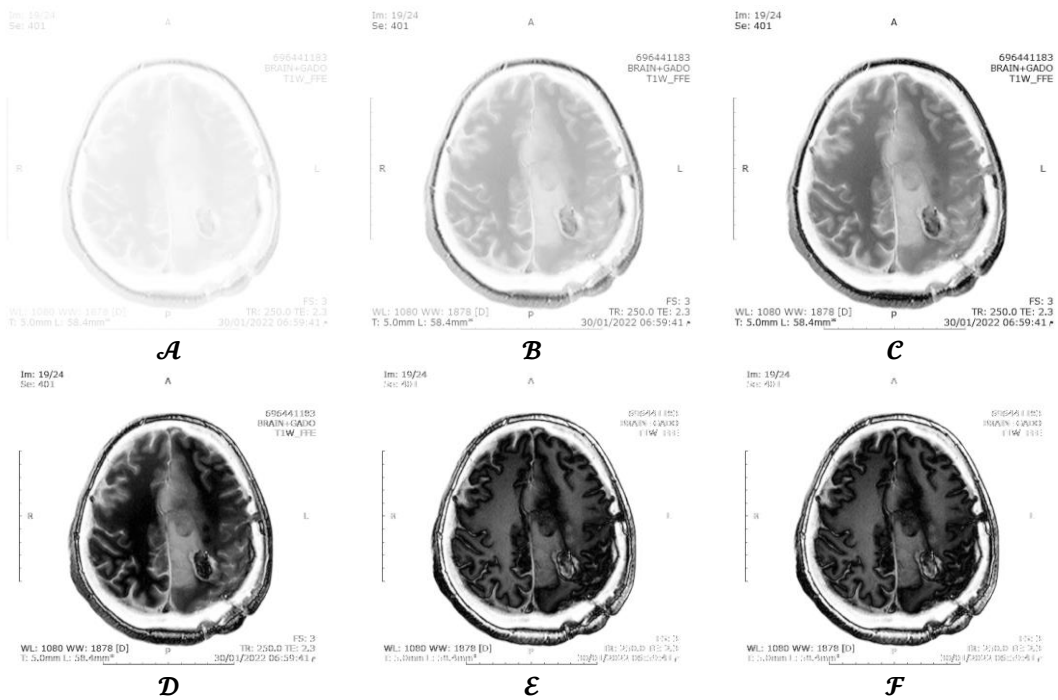


Figure 4. Histogram for X-ray images ($\mathcal{A}$) Histogram for X-ray image when $\mathcal{F}$ =0.1 ($\mathcal{B}$) Histogram for X-ray image when $\mathcal{F}$ =0.2 ($\mathcal{C}$) Histogram for X-ray image when $\mathcal{F}$ =0.3 ($\mathcal{D}$) Histogram for X-ray image when $\mathcal{F}$ =0.4 ($\mathcal{E}$) Histogram for X-ray image when $\mathcal{F}$ =0.5 ($\mathcal{F}$) Histogram for X-ray image when $\mathcal{F}$ =0.6 ($\mathcal{G}$) Histogram for X-ray image when $\mathcal{F}$ =0.7 ($\mathcal{H}$) Histogram for X-ray image when $\mathcal{F}$ =0.8 ($\mathcal{I}$) Histogram for X-ray image when $\mathcal{F}$ =0.9 ($\mathcal{J}$) Histogram for X-ray image when $\mathcal{F}$ =1 ($\mathcal{K}$) Histogram for X-ray image when $\mathcal{F}$ =1.1($\mathcal{L}$) Histogram for X-ray image when $\mathcal{F}$ =1.2



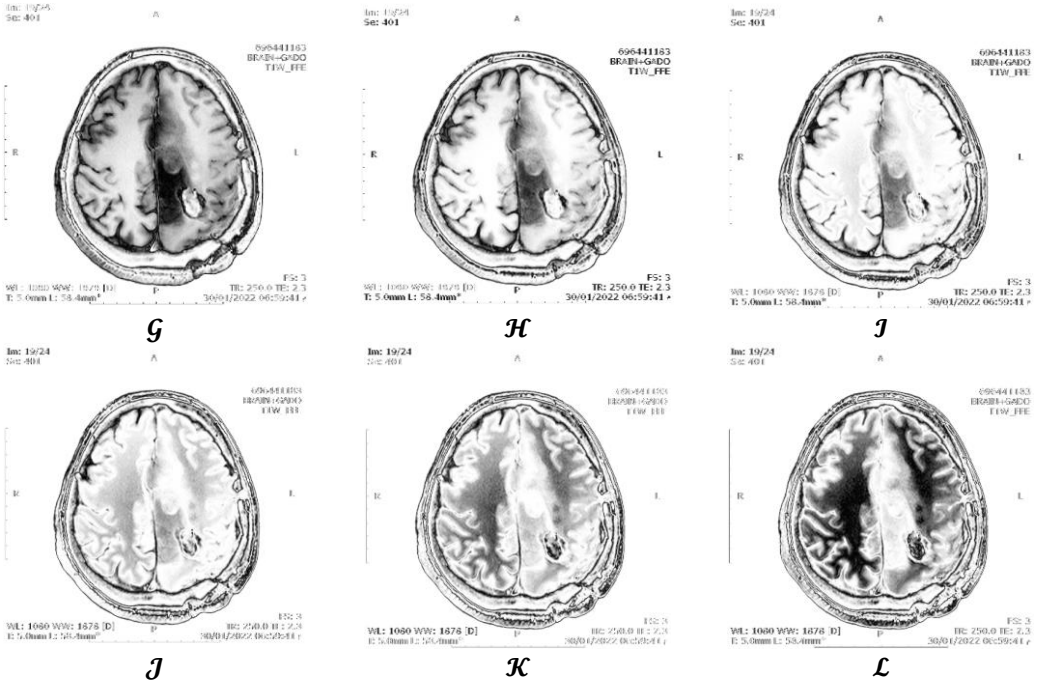
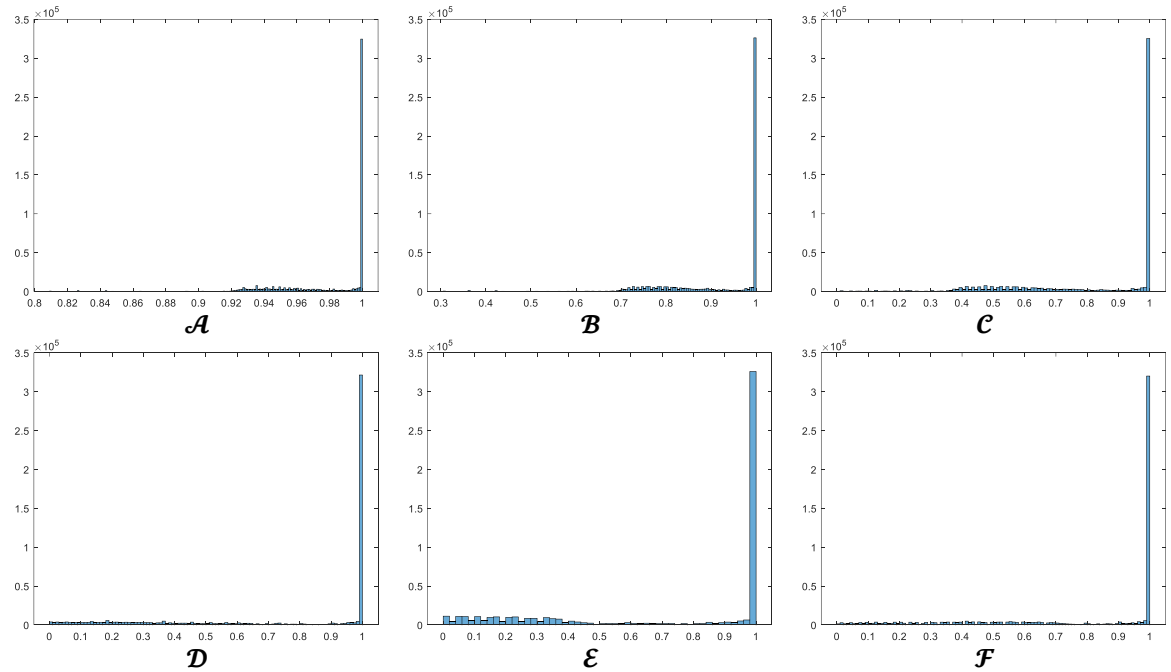


Figure 5. The resulting MRI images $\mathcal{A}$) resulting image when $\mathcal{F}$ =0.1 ($\mathcal{B}$) resulting image when $\mathcal{F}$ =0.2 ($\mathcal{C}$) resulting image when $\mathcal{F}$ =0.3 ($\mathcal{D}$) resulting image when f=0.4 ($\mathcal{E}$) resulting image when $\mathcal{F}$ =0.5 ($\mathcal{F}$) resulting image when $\mathcal{F}$ =0.6 ($\mathcal{G}$) resulting image when $\mathcal{F}$ =0.7 ($\mathcal{H}$) resulting image when $\mathcal{F}$ =0.8 ($\mathcal{I}$) resulting image when f=0.9 ($\mathcal{J}$) resulting image when $\mathcal{F}$ =1.1 ($\mathcal{K}$) resulting image when $\mathcal{F}$ =1.2($\mathcal{L}$) resulting image when $\mathcal{F}$ =0.9



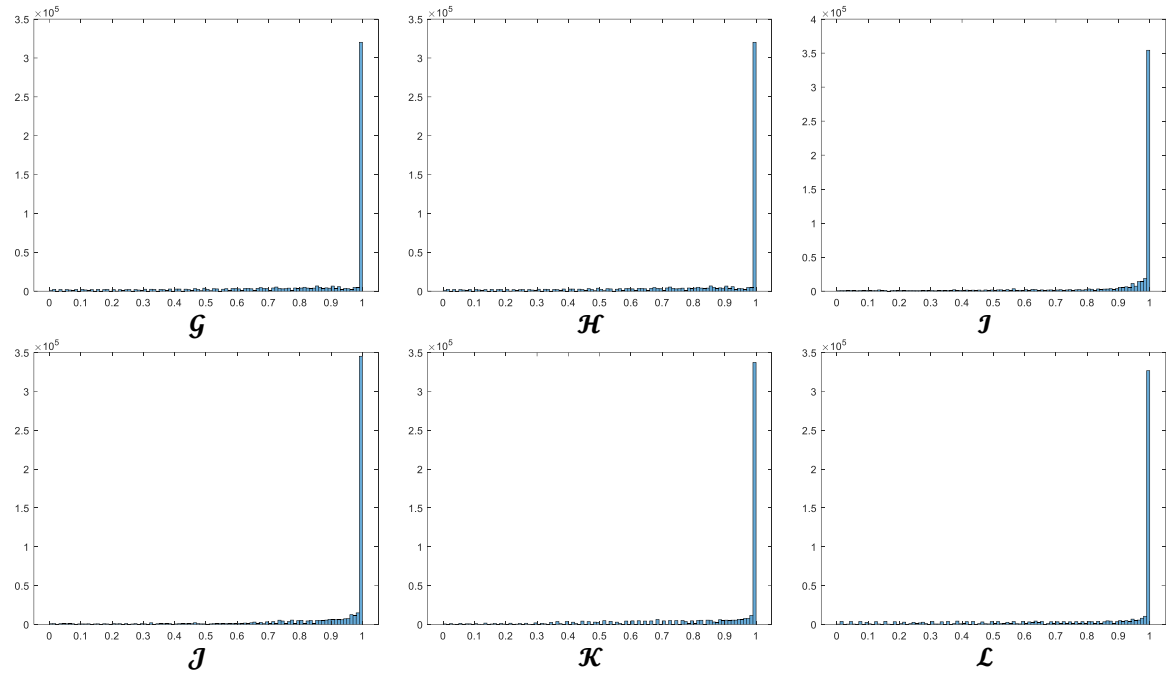
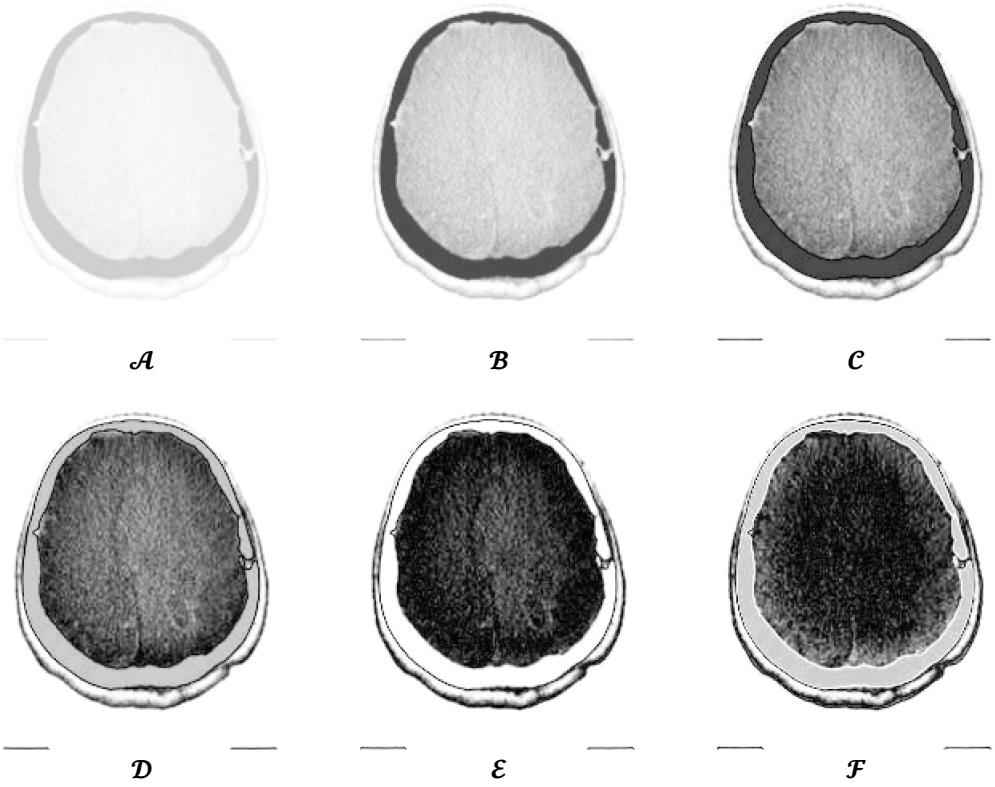


Figure 6. Histogram for MRI images ($\mathcal{A}$) Histogram for MRI image when $\mathcal{F}$ =0.1 ($\mathcal{B}$) Histogram for MRI image when $\mathcal{F}$ =0.2 ($\mathcal{C}$) Histogram for image MRI when $\mathcal{F}$ =0.3 ($\mathcal{D}$) Histogram for MRI image when $\mathcal{F}$ =0.4 ($\mathcal{E}$) Histogram for MRI image when $\mathcal{F}$ =0.5 ($\mathcal{F}$) Histogram for MRI image when $\mathcal{F}$ =0.6 ($\mathcal{G}$) Histogram for MRI image when $\mathcal{F}$ =0.7 ($\mathcal{H}$) Histogram for MRI image when $\mathcal{F}$ =0.8 ($\mathcal{I}$) Histogram for MRI image when $\mathcal{F}$ =0.9 ($\mathcal{J}$) Histogram for MRI image when $\mathcal{F}$ =1 ($\mathcal{K}$) Histogram for MRI image when $\mathcal{F}$ =1.1($\mathcal{L}$) Histogram for MRI image when $\mathcal{F}$ =1.2



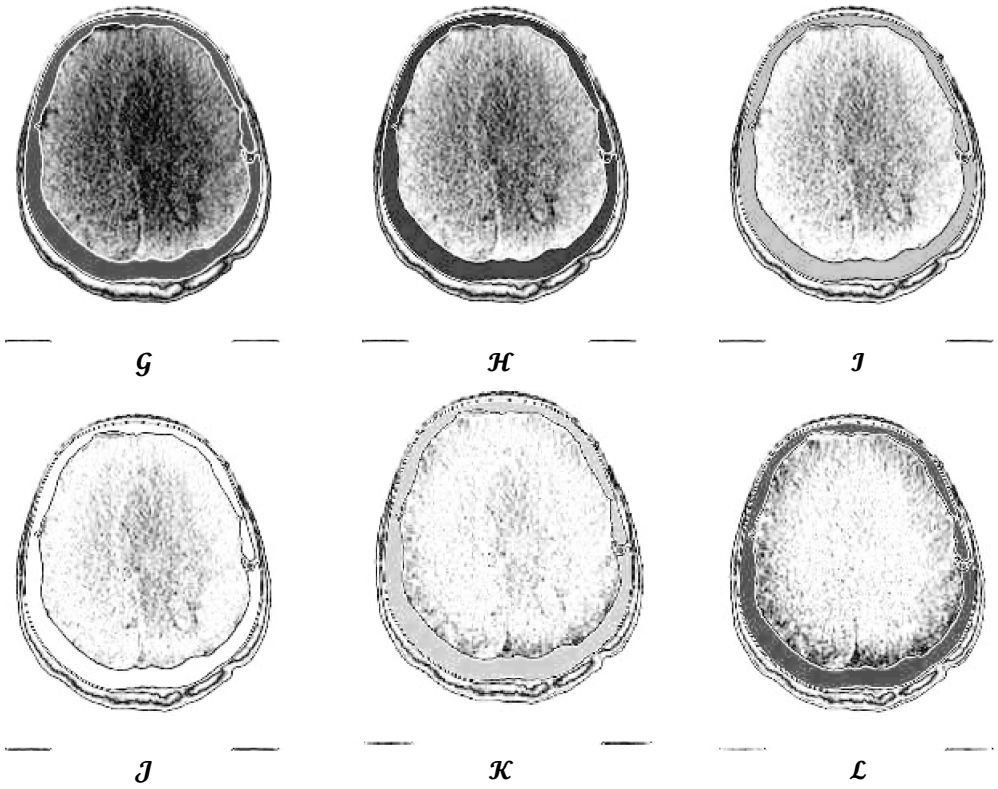
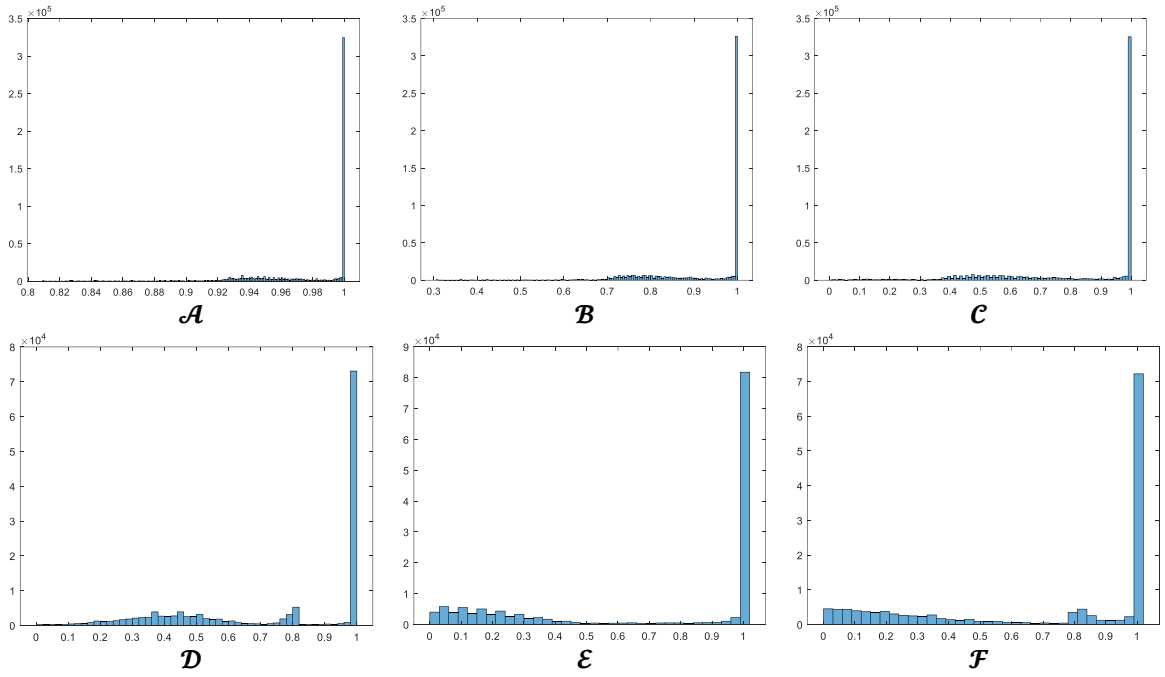


Figure 7. The resulting CT Scan images $\mathcal{A}$) resulting image when $\mathcal{F}$ =0.1 ($\mathcal{B}$) resulting image when $\mathcal{F}$ =0.2 ($\mathcal{C}$) resulting image when $\mathcal{F}$ =0.3 ($\mathcal{D}$) resulting image when $\mathcal{F}$ =0.4 ($\mathcal{E}$) resulting image when $\mathcal{F}$ =0.5 ($\mathcal{F}$) resulting image when $\mathcal{F}$ =0.6 ($\mathcal{G}$) resulting image when f=0.7 ($\mathcal{H}$) resulting image when $\mathcal{F}$ =0.8 ($\mathcal{I}$) resulting image when $\mathcal{F}$ =0.9 ($\mathcal{J}$) resulting image when $\mathcal{F}$ =1.1 ($\mathcal{K}$) resulting image when $\mathcal{F}$ =1.2($\mathcal{L}$) resulting image when f=0.9



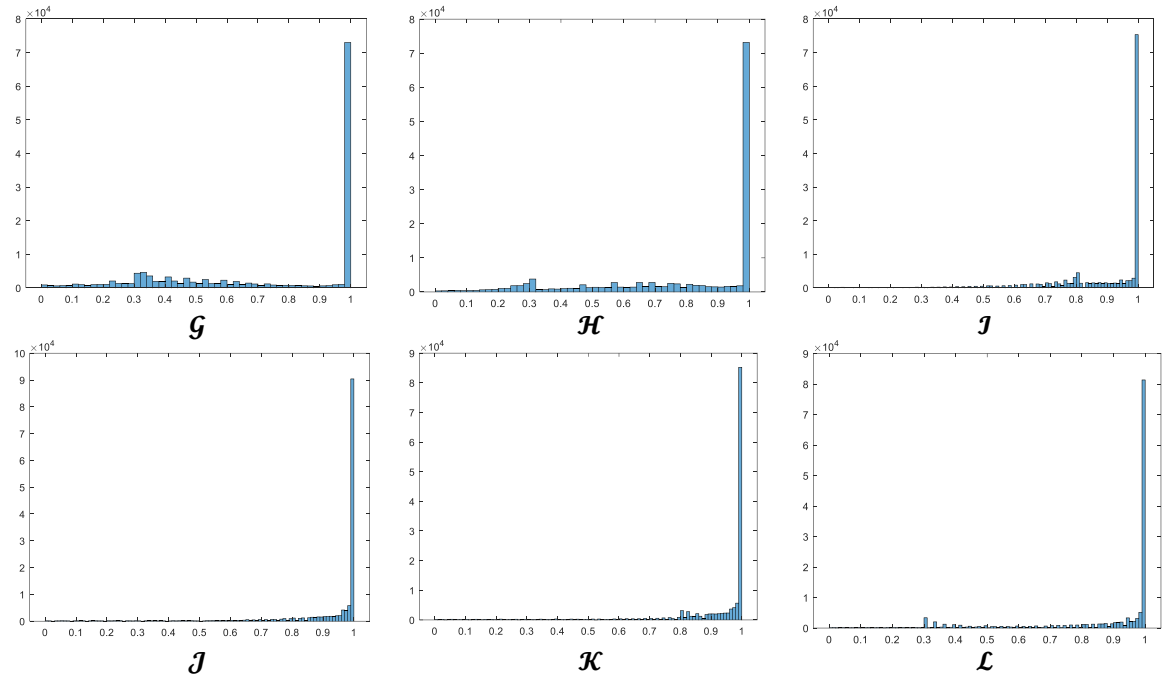


Figure 8. Histogram for CT Scan images ($\mathcal{A}$) Histogram for CT Scan image when $\mathcal{F}$ =0.1 ($\mathcal{B}$) Histogram for CT Scan image when $\mathcal{F}$ =0.2 ($\mathcal{C}$) Histogram for image CT Scan when $\mathcal{F}$ =0.3 ($\mathcal{D}$) Histogram for CT Scan image when $\mathcal{F}$ =0.4 ($\mathcal{E}$) Histogram for CT Scan image when $\mathcal{F}$ =0.5 ($\mathcal{F}$) Histogram for CT Scan image when $\mathcal{F}$ =0.6 ($\mathcal{G}$) Histogram for CT Scan image when $\mathcal{F}$ =0.7 ($\mathcal{H}$) Histogram for CT Scan image when $\mathcal{F}$ =0.8 ($\mathcal{I}$) Histogram for CT Scan image when $\mathcal{F}$ =0.9 ($\mathcal{J}$) Histogram for CT Scan image when $\mathcal{F}$ =1 ($\mathcal{K}$) Histogram for CT Scan image when $\mathcal{F}$ =1.1($\mathcal{L}$) Histogram for CT Scan image when $\mathcal{F}$ =1.2

8. Discussion

Experimental results showed that applying different F-factors directly impacted the quality of all types of medical images used in this study, including X-rays, MRIs, and CT scans.

1. As shown in **Figure 3** , which represents an enhanced X-ray image of a patient with nasal polyps using the proposed algorithm and varying F-factor values, the image is blurry, distorted, and lacks necessary detail, making diagnosis more difficult. When the F-factor values are equal to (0.4, 0.5, 0.6), the polyps begin to appear. At values of (0.7, 0.8, 0.9), the image becomes clear, and the polyps are easily visible. However, values of (1, 1.1, 1.2) result in excessive contrast enhancement, producing blurred images that can negatively impact diagnostic quality.

2. By observing **Figure 5** , which shows an enhanced MRI image of a patient with a brain tumour using the proposed algorithm and varying the F-values, the following was noted: when the F-values are equal to (0.1, 0.2), the resulting image is unclear, blurry, and lacks necessary detail, making diagnosis more difficult. As the F-values are equal to (0.3, 0.4, 0.5, 0.6), the tumour begins to appear. At F-values of (0.7, 0.8, or 0.9), the image becomes clear, and the tumour is easily visible. However, when the F-value is equal to (1, 1.1, 1.2), excessive contrast enhancement occurs, resulting in blurred images that can negatively impact diagnostic quality.

3. Similarly, **Figure 7.** presents an enhanced CT image of a patient with a brain tumour using the proposed algorithm and varying the F-values. At F-values of (0.1, 0.2), the image appears blurry, has high density, and lacks clear image details, making diagnosis more difficult. When the F-value is equal to (0.3, 0.4, 0.5, 0.6), the image is dominated by black, and the tumour is not visible. At F-values of (0.7, 0.8, and 0.9), the image becomes clear, and the tumour is easily identifiable. However, when the F-value is equal to (1, 1.1, 1.2), it results in excessive contrast enhancement, resulting in image noise, which can negatively impact diagnostic quality.

In general, F-values of (0, 0.8) have been identified as the most suitable for image enhancement in X-ray, MRI, and CT scans. It achieves the optimal balance between improving image quality and preserving original details, which contributes to increasing diagnostic accuracy and improving the interpretation of medical images. When observing the histogram in X-ray, MRI, and CT images before and after applying the enhancement algorithm, the original images displayed grey values between 0 and 1. Following the enhancement, the grey levels shifted toward higher values, or toward one, which shows how the algorithm affected the images. Contrast and lighting show that it was successful in enhancing the illumination in dim areas.

9. Conclusion

The main goal of image enhancement is to detect hidden features in images and increase the contrast in low-contrast images. These details play a crucial role in diagnosis, as some features are difficult to identify visually. Therefore, we often enhance images before displaying them. It is essential to focus on important features when displaying medical images. In this paper, an algorithm based on empirical equations is proposed, relying on trigonometric functions and varying the values of one of the main coefficients of the empirical equation F. Excellent results were obtained in diagnosing polyps in X-ray images, as well as in distinguishing brain tumours in MRI and CT scans. The best results were obtained when the F value was (0.8, 0.9). The algorithm's performance was evaluated through visual observation and histogram analysis before and after enhancement. The results showed improved contrast and detail resolution, demonstrating the efficiency of the proposed algorithm.

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Data Availability

No data was used for the research described in the article.

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Theoretical Analysis of the X-ray Mass Absorption Coefficient Produced by the Photoelectric Effect and Comparison of the Accuracy of a Computational Model of NiO and SiC

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ABSTRACT

This study aims to analyze and calculate the mass absorption coefficient of X-rays resulting from the photoelectric effect in nickel oxide and silicon carbide compounds in the energy range of 1-100 keV by using a simple, approximate, and semi-empirical theoretical model with constants that depend on the type of interaction. The effective atomic number was then calculated, and the theoretical model was used to calculate the mass absorption coefficient of the compounds. The results extracted from the application of the theoretical model were compared with the experimental or semi-experimental results extracted from the databases of the programs XCOM and FFAST. To improve the accuracy of the theoretical model, the real atomic number was replaced by the effective atomic number, as the results showed good agreement in the low energy range of the studied model. However, the accuracy of the model decreases at energies higher than 30 keV. The results were improved when using the effective atomic number, especially in the compound where there is a difference in the atomic numbers of its components. Therefore, incorporating the concept of the effective atomic number clearly enhances the accuracy of the theoretical model, making it more realistic in describing mass absorption behaviour. This simple modification to the theoretical model showed a clear improvement in the theoretical results. All calculations and graphical representations were performed using the MATLAB 2020 program.

Keywords: X-ray, absorption coefficient, effective atomic number, XCOM, FFAST, MATLAB.

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1. Introduction

Since Roentgen astonished the world with his discovery of X-rays and their ability to reveal what is hidden from the human eye, understanding their interaction with materials has become the beginning of a scientific revolution. From this point, the concept of the mass absorption coefficient emerged as a factor that determines the fate of rays, whether they are absorbed, scattered, or produced by pairs, depending on their energy and the composition of the material (Iglesias-Juez et al., 2022). This factor is considered the backbone of modern technology, as it is a crucial component in many practical applications used in everyday life. In medicine, bones can be distinguished from soft tissues due to the difference in their absorption coefficient (Abdelmonem, 2025). At airports, security inspection devices analyze the contents of bags by comparing the absorption of materials to rays. Thus, the mass absorption coefficient can be considered the link between abstract physics and solutions that harmonise our lives. From the emergency room to the nuclear control room to industrial production lines, it gives us a reality of the importance of this physical value (Hassan et al., 2021). The interaction of X-rays with materials provides information that contributes to revealing the density of electronic states, the nature of molecular bonds, and other properties of the solid state. Numerous studies in the field of materials surface science have been conducted to elucidate the properties, characteristics, and interactions associated with the surfaces of various materials (Nesterova et al., 2024). The absorption of X-rays by a material, according to specific laws, is a fundamental pillar of applied physics. Many studies have addressed the subject of X-ray absorption, the most prominent of which is the study by Mohammed Sultan Al-Buriahi and Baris T. Tonguc (2020). In their study, the researchers proposed several materials to be used as shielding materials against X-rays and other radiation. These materials are promising and can be used in windows and doors in medical diagnostic laboratories, X-ray rooms, and radiotherapy rooms (Al-Buriahi et al., 2020). In addition to the numerous studies that demonstrate the importance of the processes affecting the interaction of X-rays with matter, accurate calculations are essential for achieving a deeper and more comprehensive understanding of these processes. This enables the independent analysis of each process, followed by comparison with the theoretical model and the experimental or quasi-experimental results issued by the various programs, as indicated in the study by G. Manjula, BR. Roy, S. Jyothsna, AM. Kumar, et al., Materials Today, 2021. In this study, the researchers were able to obtain the highest absorption coefficients for the fine atomic structure region for X-ray absorption, as the results showed a discrepancy between the specified values and the measured values. The results were then compared with the results of the FFAST and WinXCom programs, as there was good agreement with the experimental and theoretical observations (Al-Buriahi et al., 2020). Advances in X-ray science have made it possible to measure the absorption of materials with high accuracy, providing profound insights into the atomic structure of materials and the extent of their density changes. This has opened up many horizons for practical applications across various fields used to test theoretical predictions. These measurements have greatly improved the ability to predict fine structure associated with X-ray absorption (Whitehead & Finke, 2021). Many practical applications also depend on this principle. For example, when using X-rays in imaging, whether in the medical or industrial field, the process relies on the difference in absorption rates when the rays interact with all parts of the material. This difference in the absorption rate makes it possible to determine the internal details of materials (Revenko & Pashkova, 2023). Relative measurements may be sufficient for theoretical calculations when calculating the mass absorption coefficient of X-rays, but measuring attenuation in general, including absorption and scattering, provides a more accurate tool for calculating the absorption coefficient of X-rays (Schweizer et al., 2024). Therefore, the aim of this research paper is to evaluate the theoretical equation and the suitability of its application when calculating the X-ray mass absorption coefficient for the studied targets, while providing a comprehensive explanation of modifying the theoretical equation in support of practical applications based on accurate absorption measurements.

2. Theoretical Background

The X-ray absorption coefficient of compounds depends on several key factors related to the compound's composition and the conditions of interaction between the material and X-rays. These include:

2. 1. The Chemical Composition of the Compound

The absorption coefficient of a compound depends on the elements that comprise it. The higher the atomic numbers of the elements, the greater the efficiency of the compound in absorbing energy.

2. 2. The Mass or Weight Fraction of the Compound

This term originates from mathematics and physics as a basis for analysing ratios. It represents the mass percentage that a particular element contributes to the overall compound, as shown in Table 1. It is used to determine the contribution of each element when calculating the overall properties of the compound, including the X-ray absorption coefficient. The weight fraction directly affects the absorption coefficient, which can be derived for each compound according to the following relationship (Bam et al., 2020; Streltsov et al.).

$$W_i = m_i/M \quad (1)$$

Where: W_i refers to the weight fraction of element i in the compound, m_i refers to the mass of element i in the compound, and M refers to the molar mass of the compound. Therefore, the mass absorption coefficient of compounds can be calculated according to the following relationship (Kasman et al., 2021)

$$[\mu/\rho]_S = \sum W_i (\mu/\rho)_i \quad (2)$$

Where: - $\sum W_i$ refers to the total weight fraction of the elements in the compound.

$[\mu/\rho]_i$ Represents the mass absorption coefficient of the element in the compound. Which is extracted from the application of the theoretical equation:

$$[\mu/\rho]_i = \rho Z^4/mE^3 \quad (3)$$

The effective atomic number can be defined as a convenient quantity for evaluating the interaction of a photon with a substance, as explained by Hine (1952). It can provide a preliminary estimate of the chemical composition of a substance in general. The effective atomic number is large for inorganic compounds and metals, while it is small for organic materials. It is also called the effective charge and can be defined as the number of electrons per unit mass of the absorber. The effective atomic number is symbolised by the symbol Z_{eff}. Its value can be calculated either using a physical law or Slater's rule. It is a suitable parameter for representing the interactions of X-rays and gamma rays. For example, it is used in radiation shielding designs or in calculating the absorbed dose in radiotherapy (Zhou, 2024). Slater was able to calculate the effective nuclear charge (effective atomic number) of electrons in the s, p, d, and f shells (Cheewasukhanont et al., 2022). It is necessary to determine the amount of X-rays absorbed by materials in order to determine the amount of safe dose for individuals, through which the most appropriate materials are chosen for use as radiation shields. In the case of compounds, Slater's rule cannot be applied to extract the effective atomic number. Rather, a more accurate mathematical relationship can be used to calculate the effective atomic number based on the mass fraction of the elements that make up the compound, according to the following relationship (Aldalawi et al., 2021):

$$Z_{eff} = \sum W_i Z^3 \quad (4)$$

Table. 1. shows the most important physical and chemical properties of (NiO, SiC) (Patel, 2023)

Symbol	Density	Molecular weight	Boiling point	Melting point	Crystal structure	Effective atomic number
NiO	6,67	74.69	2800	1955	FCC	25.89
SiC	3.21	40.10	Transcends	2700	FCC	12.57

3. Research Methodology

In this research paper, the mass absorption coefficient of X-rays in the energy range of 1-100 keV was calculated based on photoelectric absorption for the compounds SiC and NiO, as well as the elements that make up the compounds (Si, C, Ni, O). This analysis aims to investigate the absorption behaviour resulting from the photoelectric effect for theoretical purposes and to highlight the influence of atomic number and energy on the absorption capacity of materials. To develop a theoretical model based on photoelectric absorption, the calculations were performed using theoretical equations (2) and (3).

The mass absorption coefficient of the target materials was extracted using standard programs approved by NIST, such as XCOM. XCOM has its roots in the early 1970s, when physicists at the National Institute of Standards and Technology (NIST) developed computational models to calculate the cross sections of photon interactions with matter. It was published as a standalone program in 1987 by Berger & Haberman and later updated. XCOM is a specialized program for calculating the absorption coefficients of X-rays in various materials. Its name reflects the combination of the concept of X-rays and the complex calculations associated with them. It was developed by the NIST Laboratory for Calculating the Absorption Coefficients of X-rays in Various Materials (Berger, 2010), along with the FFAST program.

FFAST is a physics-based computer program that serves as a standard reference database developed by the National Institute of Standards and Technology (NIST), last updated in 2005, which contains a detailed table of atomic form factors, absorption cross-section, electro-optical scattering, and mass attenuation coefficients for the range (1-10 eV), the range (-0.4 - 1 MeV), and the atomic range (1-92). Much of the modern theoretical foundation for this data was provided by Cromer, Mann, and Lieberman, while Heky et al. contributed significant experimental data. FFAST is an abbreviation for (Form Factor and Scattering Tables). The program was developed to meet the need for accurate and up-to-date tables of physical parameters related to the interaction of X-rays with materials. This program began in the mid-twentieth century, and with the development of technology, FFAST emerged as an updated tool to obtain higher accuracy and efficiency, using the latest physical theories and practical data to obtain results that meet modern needs. FFAST was developed as an alternative to the XCOM program, but it focuses primarily on diffraction, scattering, and interference. It began in the early 1990s and was developed using new computational methods, including quantum calculations. The program has several functions, including calculating the absorption coefficient of X-rays for single elements, compounds, and mixtures. Further, FFAST provides accurate scientific information about the interaction of matter with X-rays and plays an effective role in the design of X-ray devices, medical imaging, and scientific studies related to radiation. It is widely used in absorption and scattering calculations, as it covers a wide energy range (1 keV - 100 MeV) (Factor, 2009).

The effective atomic number or effective nuclear charge was calculated using a theoretical equation based on the atomic number and mass fraction of the compound. The original atomic number was then replaced by the effective atomic number. The results were then tabulated and represented graphically, and a comparison was made between all the results obtained by different methods. All calculations were performed using MATLAB 2020. As shown in **Figures 1**.

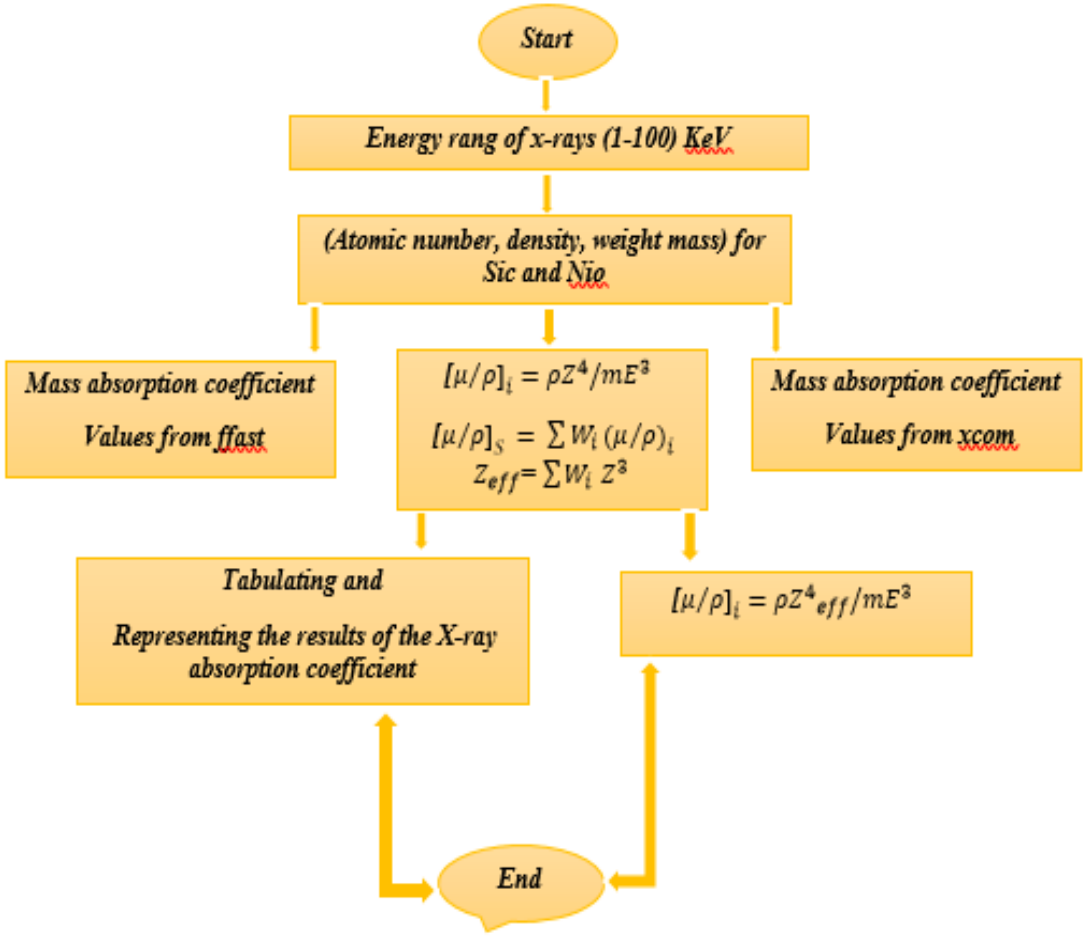

Figure 1. Illustrates the MATLAB algorithm.

4. Results and Discussion

Figures 2 and 3, as well as Tables 2 and 3, show the values of the mass absorption coefficient according to Equation (2) for NiO-Z and SiC-Z, which represent the value of the mass absorption coefficient of X-rays according to the theoretical model studied in terms of the atomic number. The results are compared with data from the XCOM and FFAST programs. From the figure, we note that the mass absorption coefficient is very high in the low range, indicating strong absorption of photons in the low range. As the energy increases, a sharp decrease occurs due to the diminishing influence of the photoelectric effect. At high energies, the absorption coefficient stabilizes at low values, where the dominance of the Compton Effect and pair production becomes apparent. Irregularities are also observed in the absorption edges, which may be attributed to several factors, including the chemical effects resulting from the combination of pure nickel with oxygen and interactions between various physical phenomena. Additionally, the mass absorption coefficient of silicon carbide increases significantly in the low range due to the dominance of the photoelectric effect. In this range we see the conformity of the curve of theoretical equation(2) with the experimental results of the XCOM program.

Then the coefficient begins to decrease significantly, which shows that the results of the equation agree well with the data of *the* XCOM program at medium energies (10-50 keV). At high energies < 50 keV, we notice an increasing and gradual decrease in the values of the mass absorption coefficient, but all the curves are very close in the high-energy range, but we notice that the experimental values of the XCOM program are closest to the results of equation (2). At high energies (<40 keV), we notice that the theoretical values are closer to the experimental values, meaning that in this range the mass absorption coefficient becomes more stable, which reflects that the effects of the electronic structure in this range have begun to decrease. Specifically, compounds that consist of elements with significantly different atomic numbers will have theoretical values that deviate from

the experimental values, whereas compounds that contain elements with similar atomic numbers will have theoretical values that are close to the experimental values. The shielding coefficient of the target compounds (NiO, SiC) was determined by calculating the amount of shielding caused by the inner electrons close to the nucleus on the electrons in the other outer orbits. Based on this calculation, the effective atomic number (effective charge) was measured theoretically according to Equation (4) for the studied compounds. The mass absorption coefficient of the above metals was calculated according to Equation (3), replacing the atomic number (Z) with the effective atomic number (Z_{eff}), which was extracted according to Equation (4). We note the curve of the mass absorption coefficient as a function of energy for nickel oxide. In the low energy range (0-20 keV), its values, according to Equation (2), NiO-Z, are higher than the rest of the curves and tables, indicating greater absorption of X-rays in this range. As for the results of the modified equation in terms of the effective atomic number, NiO-$Z_{eff} for\ the\ compound$, both the results and the curve indicate a sharp decrease in the mass absorption coefficient. This means that when using the effective atomic number instead of the atomic number, the absorption of X-rays by the material decreases. In the medium energy range (20-50 keV), we note that the values extracted from Equation (4) are higher than the experimental values of the XCOM program, and the values of the modified equation (NiO-Z_{eff})are lower than the experimental values of the XCOM program. However, this difference between the curves gradually decreases as the energy increases. In the high energy range (50-100 keV), we note a greater convergence between the curves and the values of the models used, but (NiO-Z_{eff}) remains the lowest of the curves. The reason for the decrease can be explained by the fact that the model used does not accurately reflect the effects of each element. The model also neglects sharp transitions in absorption in the energy range used. In addition, the effective atomic number is an approximation and is not an accurate replacement for the original equation. Therefore, when using it, precise details of X-ray absorption may be lost for some compounds. At low energies (less than 5 keV), oxygen contributes significantly, giving a good approximation to the equation. In Fig. 1 and Table 3, we observe that (SiC) at low energy ranges (0-20 keV) takes a representation similar to nickel oxide, where the curve and values of (SiC-Z) resulting from applying Equation (2) are higher than the rest of the curves, while (SiC-Z_{eff})resulting from modifying Equation (4) are less than XCOM. At medium energies (20-50 keV), we observe convergence in the plots and values between the models used, except for the XCOM program, which remains gradually lower. At high energies (50-100 keV), the curves converge or begin to converge, but (SiC-Z_{eff})remains slightly lower. In addition, the differences at the high range between the studied models become smaller. The reason for this is that silicon carbide shows a different response in absorbing X-rays in a way that affects the computational models. In fact, at low energies, the shielding is more pronounced, leading to a decrease in the effective atomic number and, consequently, a decrease in the absorption coefficient value. The mass is compared to the value calculated according to equation (4). At medium energies, the effect of shielding begins to decrease until the effective atomic number remains less than the normal atomic number. We note that the decrease in the value of the mass absorption coefficient remains less than it was in the case of using the normal atomic number. At high energies, the most important role is in the absorption of the inner electrons, as we note a decrease in the differences between Z and Z_{eff} . At that time, the effect of replacing one of the factors of the theoretical equation (3) is very small in the high-energy range due to the dominance of Compton interactions and pair production in the material.

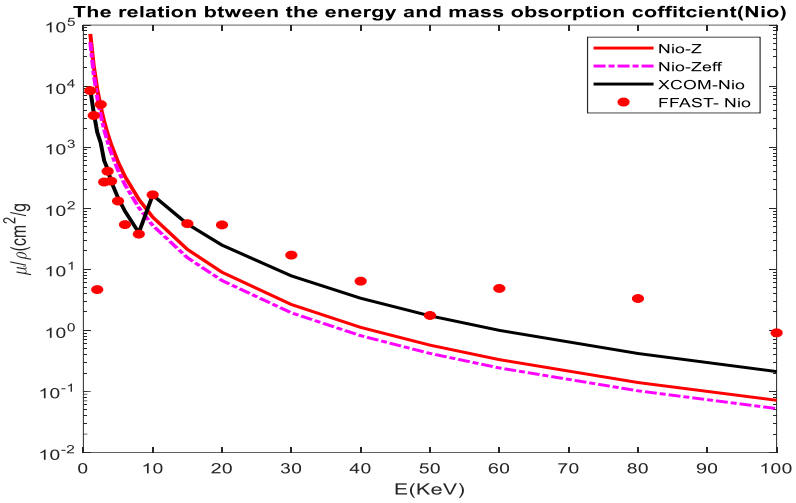

Figure 2. shows the mass absorption coefficient of nickel oxide using various computational and experimental methods.

Table 2. Shows the theoretical and experimental values of the X-ray absorption coefficient as a function of energy for nickel oxide.

Energy (keV)	Absorption coefficient of X-ray by NiO- Z(cm^2/g)	Absorption coefficient of X-ray by NiO- $Zeff$ (cm^2/g)	Absorption coefficient of X-ray by XCOM (cm^2/g)	Absorption coefficient of X-ray by FFAST (cm^2/g)
1	71577.4	52347.8	8723	8428.158
1.5	21208.1	15510.4	3655	3297.925
2	8947.18	6543.4	1755	4.653303
2.5	4580.95	3350.2	1177.9	5005.26
3	2651.01	1938.8	600.8	268.8943
3.5	1669.44	1220.9	437.9	403.5981
4	1118.39	817.93	275	277.6821
5	572.619	418.78	148.70	131.211
6	331.377	242.35	89.5	53.9435
8	139.799	102.24	39.83	37.6931
10	71.5774	52.347	164.2	165.8165
15	21.2081	15.510	55.21	55.933
20	8.94718	6.5434	24.88	53.3352
30	2.65101	1.9388	7.801	17.0735
40	1.11839	0.8179	3.358	6.3902
50	0.57261	0.4187	1.73	1.753
60	0.33137	0.2423	0.9994	4.8594
80	0.13979	0.1022	0.4178	3.3207
100	0.07157	0.0523	0.2113	0.911

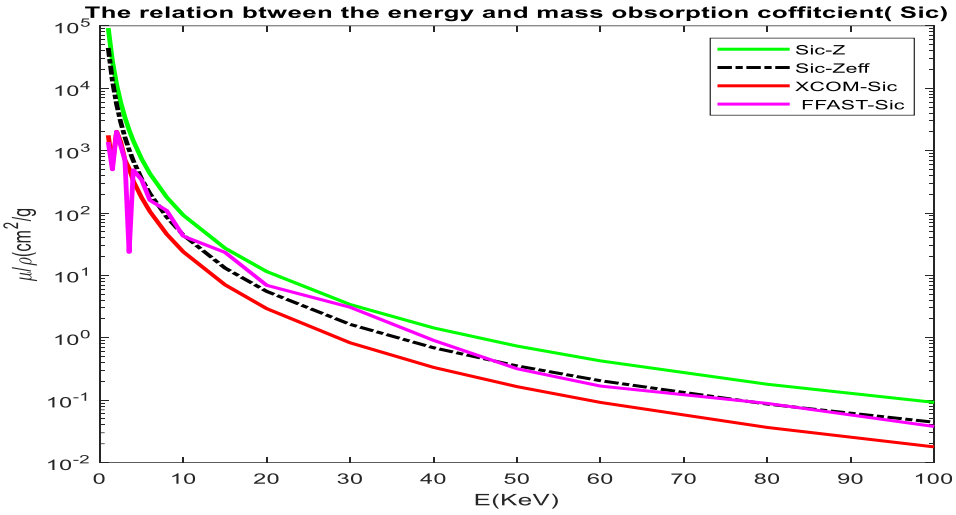

Figure 3. shows the mass absorption coefficient of silicon carbide using various computational and experimental methods

Table 3. Shows the theoretical and experimental values of the X-ray absorption coefficient as a function of energy for silicon carbide.

Energy (keV)	Absorption coefficient of X-ray by SiC-Z(cm^2/g)	Absorption coefficient of X-ray by SiC-$zeff$ (cm^2/g)	Absorption coefficient of X-ray by XCOM (cm^2/g)	Absorption coefficient of X-ray by FFAST (cm^2/g)
1	2295.814	2852.8	1760	1373.385
1.5	680.2412	845.28	583	493.3119
2	286.9767	356.60	2034	2020.3
2.5	146.9321	182.58	1372.5	1191.3
3	85.03015	105.66	711	704.55
3.5	53.54668	66.538	519.15	23.366
4	35.87209	44.575	327.3	491.6185
5	18.36651	22.822	176.4	339.921
6	10.62876	13.207	105.3	159.6442
8	4.484012	5.5719	45.95	109.4068
10	2.295814	2.8528	23.84	42.4616
15	0.680241	0.8452	7.066	23.366
20	0.286976	0.3566	2.929	6.9286
30	0.085030	0.1056	0.8301	3.0826
40	0.035872	0.0445	0.3349	0.9081
50	0.018366	0.0228	0.1647	0.3188
60	0.010628	0.0132	0.09195	0.1681
80	0.004484	0.0055	0.03652	0.0887
100	0.002295	0.0028	0.01781	0.0378

5. Conclusions

When studying and calculating the X-ray mass absorption coefficient for the two compounds in this study within the energy range (1-100 keV), it becomes clear that there is a fundamental discrepancy in using the effective atomic number instead of the real atomic number. When using nickel oxide, which consists of two elements with a difference in atomic number, this difference leads to a small and non-linear interaction, as nickel has a significant effect at the absorption edge energies, i.e., in the low energy

range. In addition, oxygen atoms have a prominent role in the overall absorption of the compound, which makes replacing the real number with the atomic number, i.e., by modifying the equation, very useful to obtain an idea of the average absorption behaviour. However, this idea is less accurate in the high-energy range, especially at the absorption edges of nickel, where sharp discrepancies appear in the values of the mass absorption coefficient, which cannot be represented using the effective atomic number alone.

Therefore, we conclude that modifying the equation is appropriate and useful for obtaining an approximate estimate away from the absorption edges, while using the real atomic number is useful and necessary in cases that require spectral accuracy. As for silicon carbide, which is composed of two relatively light elements, the absorption curve is more consistent and regular in the studied energy range. The absence of absorption edges in the medium and low energy range of X-rays gives a highly accurate prediction when using the effective atomic number to obtain a consistent absorption behaviour. This makes silicon carbide easier to represent both physically and behaviourally in applications that need a general estimate of absorption and do not require a precise interpretation of the spectrum.

Consequently, we conclude that it is preferable to use the true atomic number, as general approximations, and the effective atomic number in precise spectroscopic analyses, particularly for absorption edges for nickel oxide. For silicon carbide, using the effective atomic number from the modified theoretical equation is considered more accurate and appropriate, due to its simple atomic structure and the absence of absorption edges in the compound.

Conflicts of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Stress, Sources, and Coping Strategies Among Nursing Students in the West Bank: A Cross-Sectional Study

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ABSTRACT

Nursing students in the West Bank face numerous stressors that affect their academic performance and mental health, ranging from academic workload to sociopolitical challenges unique to the region. This study aims to explore stress levels, identify sources of stress, and evaluate the coping strategies used by nursing students in the West Bank. A cross-sectional design was employed using a convenience sample of 385 nursing students enrolled in diploma and baccalaureate nursing programs across Palestinian universities and colleges in the West Bank. Data were collected through an online self-administered questionnaire composed of demographic data, the Perceived Stress Scale (PSS), a stressors checklist, and the Brief COPE inventory. Descriptive and inferential statistics were used for data analysis using SPSS version 27. The majority of students (93.4%) experienced moderate stress, with primary sources including academic workload, financial difficulties, and future uncertainties. The most utilised coping strategies were self-distraction, acceptance, and humour. Significant stress differences were observed based on gender, academic year, parental education, and employment status ($p<0.05$). Nursing students in the West Bank experience substantial stress, influenced by both academic and socio-political factors. Intervention programs tailored to student needs, including stress management training and financial support, are necessary to foster resilience and academic success.

Keywords: Stress, Nursing Students, Coping Strategies, West Bank Perceived.

1. Introduction

Globally, stress is recognised as a major public concern, impacting an estimated one-third of people while also leading to a myriad of bodily and health complications (Organization, 2022). Among university students, those studying in categorically demanding programs like nursing are even more at risk. They struggle with relentless academic pressure, emotionally draining clinical experience, and performance expectation workloads, which lead to significantly higher levels of stress than students in other fields (Bolarinwa & Ishola, 2023; Xu et al., 2023). If left unaddressed, chronic stress in nursing students may result in serious untreated health complications such as anxiety, burnout, and even dropping out from school (Boamah et al., 2024).

The rigour of nursing education involves not only mastering the theoretical knowledge and clinical skills but also considerable emotional labour. As nursing students engage in clinical placements, they regularly face human suffering while still navigating coursework and personal life at home (Sharif & Masoumi, 2005). Notably, many students develop positive coping skills, which are helpful for their overall health and educational successes; however, not all students have emotional coping resources or institutional support to develop them (Jimenez et al., 2010). This indicates that nursing programs must provide psychological support to nursing students in addition to skills-based knowledge and training.

Nursing students in the West Bank are especially encumbered by a higher register of stress in addition to the academic and clinical stress that all nursing students experience due to political strife and resource-poor environments. In addition to negotiating the emotional trouble that accompanies academic pressures, nursing students in the West Bank also contend with daily realities such as political conflict, economic instability, limited movement, and community-level trauma (Abu-Raiya & Pargament, 2015; Salameh et al., 2025; Thabet et al., 2008). These realities multiply their emotional burden and make it very hard to persist and thrive in their education. For many students, adjusting to the broader social and political environment and surviving are more important than keeping up academically.

Even with these complications, many students still use personal, social, and cultural resources to cope. Family support, religious faith, friends, and cultural values can protect against the ill effects of stress, while problem-solving ability and positive thinking may contribute to resilience (Agbaria & Abu-Mokh, 2023; Lazarus & Folkman, 1984; Loureiro et al., 2024). There are also unproductive coping strategies. Some students may engage in avoidant behaviour or denial that will ultimately contribute to increasing levels of stress (Seyedfatemi et al., 2007).

The purpose of this study is to examine the stress level, stressors of stress, and coping mechanisms of nursing students in the West Bank, where they are exposed to a unique combination of academic, clinical, and geopolitical influences that contribute to their psychological distress. These students often have the responsibility of providing safe and effective patient care while experiencing psychological discomfort. They are also expected to distinguish between anxiety caused by their academic responsibilities and that resulting from living and schooling in a politically unstable location (Li et al., 2024). Their limited support systems, combined with exposure to traumatic events, act as psychosocial potential health threats to their academic and emotional growth (Li et al., 2024). Prolonged exposure to stress is widely known to produce psychological distress, including anxiety, depression, and burnout, not to mention interfere with their academic performance (Pulido-Martos et al., 2012). Unfortunately, very few empirical studies have examined the lived experiences of nursing students, their stress responses, and factors impacting their distress (Hamaideh et al., 2024).

It is important to determine how nursing students view and cope with stress in order to promote academic resilience and mental health support. Without such information, nursing programs could be ineffective in preparing students for success, both in clinical practice and on a personal level, even in the safest environments. They need to understand these aspects of effective nursing education to ensure that students are utilizing best practices in a high-risk area, where stress is an environmental situation that is unavoidable and ongoing (Seyedfatemi et al., 2007). This research fills this gap in the literature by examining the stress

experienced by nursing students in the West Bank and identifying their levels of stress, sources of stress, and coping techniques employed (Bolarinwa & Ishola, 2023).

Based on the results of this research, it is anticipated that new culturally relevant interventions and institutional policies will emerge within institutions to foster student mental health in areas of conflict (Alzayyat & Al-Gamal, 2014). Increased awareness of psychological processes and the negative outcomes of stress on this student cohort will lead to the implementation of tailored intervention strategies at each institution, including appropriate adaptive learning environments, mentorship strategies, and emotional support systems (Gibbons et al., 2011). These will not only contribute to the academic success of students enrolled in coursework and programs with these challenges, but they will also contribute to students becoming clinically competent and students who will be emotionally and mentally ready to enter nursing roles in less than desirable healthcare situations.

In areas with limited resources and political instability, this study adds to the global discourse on nursing student stress and mental health by drawing attention to a population that has received little attention in the literature (Custer Jr, 2010; Organization, 2022). The findings of the research may assist education and health care policymakers, organisations, and institutions in considering interventions that directly respond to the particular needs of nursing students in the West Bank (Li et al., 2024). Ultimately, supporting those students' well-being and resilience is a step toward establishing a more sustainable, compassionate, and effective healthcare workforce for the region.

General Objective

To investigate the stress experiences level, sources of stress, and coping strategies among nursing students in the West Bank.

Specific Objectives

The specific objectives of this study are to:

1. Identify the types of stress experiences encountered by nursing students in the West Bank.
2. Examine the primary sources of stress that contribute to challenges among nursing students in the West Bank.
3. Explore the coping strategies employed by nursing students in the West Bank to manage and alleviate stress.
4. Investigate the differences between demographic characteristics (such as age, gender, academic year, and socioeconomic status) and the level of stress experienced by nursing students in the West Bank at alpha <0.05.

Research Questions

This study aims to answer the following research questions:

1. What is the level of stress reported by nursing students in the West Bank?
2. What are the main sources of stress contributing to the challenges faced by these students?
3. What coping strategies do nursing students in the West Bank use to manage stress?
4. Are there statistically significant differences between demographic characteristics and the level of stress experienced by nursing students?

Research Hypothesis

Null Hypothesis (H_0): There are no statistically significant differences in the level of stress experienced by nursing students in the West Bank based on demographic characteristics such as age, gender, and level of education at an alpha level ($\alpha \leq 0.05$).

Alternative Hypothesis (H_1): There are statistically significant differences in the level of stress experienced by nursing students in the West Bank based on demographic characteristics such as age, gender, and level of education at an alpha level ($\alpha > 0.05$).

2. Methodology

This chapter describes the study's methodology, which includes the population, setting, sampling strategy, inclusion and exclusion criteria, research design, data collection techniques, tool validity and reliability, ethical considerations, and data analysis plan.

2. 1. Study Design

A cross-sectional descriptive design was employed in this study to assess the stress levels, causes, and coping strategies of nursing students in the West Bank who were enrolled in bachelor's and diploma programs. This design is particularly well-suited for documenting participants' experiences at a specific point in time and is commonly employed for observational research within the social and health sciences (Polit & Beck, 2008).

2. 2. Study Setting

The research took place in several well-respected schools and universities across the West Bank that offer nursing bachelor's and diploma programs. Students from diverse socioeconomic and academic backgrounds had the opportunity to engage in a rich and inclusive environment.

2. 3. Study Time Frame

Data collection took place over a span of 20 days, from March 4 to March 24, 2024. This timeframe was chosen to ensure the collection of a representative sample and to maintain quality control throughout the data processing phase. It is noteworthy that this period coincided with localised unrest and increased political activity, which might have impacted students' stress levels.

2. 4. Study Population

The target group for this study was around 20,000 nursing students who were enrolled in diploma and bachelor's degree programs across the West Bank during the 2023–2024 academic year, according to the Palestinian Central Bureau of Statistics (PCBS, 2024). This figure includes students from both public and private higher education institutions.

2. 5. Sampling Technique and Sample Size

A convenience sampling method was employed to recruit participants based on their availability and willingness to participate. The sample size was calculated using G*Power 3.1 software (Faul et al., 2007) for a one-way ANOVA, with a medium effect size of 0.3, a 95% confidence interval (CI), and a significance level of $\alpha = 0.05$. Based on this calculation, a minimum of 380 participants was deemed sufficient. To account for potential non-response or attrition, an additional five students were included, bringing the final sample size to 385 nursing students.

2. 6. Inclusion and Exclusion Criteria

2. 6. 1. Inclusion Criteria

- Nursing students currently enrolled in accredited diploma or bachelor's nursing programs in the West Bank.
- Students who voluntarily consented to participate in the study.

2. 6. 2. Exclusion Criteria

- Students who were on leave or absent during the data collection period.
- Students enrolled in postgraduate programs (master's or PhD).

2. 7. Data Collection Tool

Data was collected using a structured self-administered questionnaire, adapted from previous studies (Bolarinwa & Ishola, 2023), and consisted of four main sections:

- ***Section 1:*** Socio-demographic characteristics (e.g., age, gender, academic year, and residence).
- ***Section 2:*** The Perceived Stress Scale (PSS-10) in Arabic, which measures the degree to which situations in one's life are appraised as stressful (Ali et al., 2021).
- ***Section 3:*** A list of potential sources of stress, where students marked whether they had experienced each stressor.
- ***Section 4:*** The Brief COPE inventory, which assessed the coping strategies used by the students.

2. 8. Cut-off Points for Stress Levels

Stress levels were categorised based on mean scores from the PSS:

- Low stress: 1.00 – 2.3
- Moderate stress: 2.34 – 3.67
- High stress: 3.68 – 5.00

2. 9. Data Collection Procedure

The questionnaire was distributed electronically via Google Forms to nursing students across various institutions. Participation was voluntary, and a convenience sampling technique was used to facilitate broad participation.

2. 10. Validity and Reliability of the Instrument

To ensure face validity, the questionnaire was reviewed by subject matter experts in nursing education and mental health. Reliability testing was conducted using Cronbach's alpha, which yielded a coefficient of 0.80 for the PSS—indicating good internal consistency. Additionally, a pilot study involving 40 students (10% of the total sample) was conducted to evaluate the clarity and feasibility of the instrument. Results indicated that the questionnaire was well understood and took approximately 15 minutes to complete.

2. 11. Data Analysis

Data were analysed using SPSS version 27. After ensuring data integrity and normality, both descriptive and inferential statistics were applied. Descriptive statistics (frequencies, percentages, means, and standard deviations) summarised participant characteristics and variable distributions. Inferential tests such as the independent t-test and one-way ANOVA were used to assess differences in stress levels across demographic groups.

2. 12. Ethical Considerations

The study upheld high ethical standards throughout:

- Confidentiality was maintained by anonymizing responses and securely storing data.

- Anonymity was protected by avoiding the collection of identifying information; instead, coded data was used for analysis.
- Participants were informed of the study purpose, their right to withdraw, and that their responses would remain confidential and used solely for academic purposes.

2. 13. Ethical Approval

Ethical approval was obtained from the relevant Institutional Review Board (IRB) prior to data collection. The IRB reviewed the study's protocol to ensure alignment with ethical principles, including informed consent, participant welfare, and data privacy.

3. Results

A total of 385 participants were involved in the study. The gender distribution was almost evenly matched, with 50.8% male (n = 193) and 49.2% female (n = 187). The age distribution generally skewed toward younger respondents, with the majority of participants aged 18–20 years (43.9%) and 21–23 years (37.9%). Only 8.9% were in the 24–26 age category, and 9.2% were 27 years or older.

Concerning education, the majority of participants (66.8%) reported that they had a bachelor's degree, while 33.2% reported holding a diploma. Participants were evenly distributed across academic years: 25.0% reported being in their first year, 26.6% in their second year, 16.8% in their third year, and 31.6% in their fourth year. The household composition suggests that the majority of participants live in towns or villages (58.9%), while 29.7% reported living in cities and 11.3% in refugee camps.

In terms of marital status, 71.3% of participants were single; 16.1% were married; 7.4% were divorced or separated; and 5.3% were widowed. When participants indicated dependent children, 49.5% reported having 1–2 dependents, 32.6% reported having no dependent children and, 17.9% reported having three or more. In terms of parental education, 29.2% of fathers and 26.6% of mothers had no formal schooling, while 41.1% of fathers and 35.8% of mothers had completed high school. Employment status revealed that 60.5% of participants were unemployed, 24.2% were employed full-time and 15.3% part-time. With respect to household income, 35.5%, fell below 1800 NIS, 25.8% earned 1800–2700 NIS, 19.5% earned 2700–4000 NIS and 19.2% earned above 4000 NIS.

The majority of participants (78.9%) live at home with their parents. With respect to academic performance, the data indicated 42.9% of participants reported a cumulative average between 70–79.9%; 15.0% a cumulative average between 60–69.9%; 24.7% a cumulative average between 80–89.9%; and 8.7% reported a cumulative average over 90%. Lastly, most participants (62.6%) were enrolled in colleges and (37.4%) in universities. As shown in Table 1.

Table 1: Demographic Variables of the Participants (n=385)

Demographic variable		n	%
Gender	Male	193	50.8%
	Female	187	49.2%
Age	18-20 Years Old	167	43.9%
	21-23 Years Old	144	37.9%
	24-26 Years Old	34	8.9%
	27 Years Old and Above	35	9.2%
Level of Education	Diploma	126	33.2%
	Bachelor's Degree	254	66.8%
Years of the study	First Years	95	25.0%
	Second Years	101	26.6%
	Third Years	64	16.8%

	Fourth Years	120	31.6%
Location of Residence	Major City (e.g., Ramallah, Nablus)	113	29.7%
	Town/Village	224	58.9%
	Refugee Camp	43	11.3%
Marital Status	Single	271	71.3%
	Married	61	16.1%
	Divorced/Separated	28	7.4%
	Widowed	20	5.3%
Number of Dependents	None	124	32.6%
	1-2	188	49.5%
	Or More	68	17.9%
Highest Level of Education (father)	No Formal Education	111	29.2%
	High School	156	41.1%
	Diploma	35	9.2%
	Bachelor's Degree	60	15.8%
	Master's Degree or Higher	18	4.7%
Highest Level of Education (mother)	No Formal Education	101	26.6%
	High School	136	35.8%
	Diploma	76	20.0%
	Bachelor's Degree	52	13.7%
	Master's Degree or Higher	15	3.9%
Employment Status (If Applicable)	Employed Full-time	92	24.2%
	Employed Part-timer	58	15.3%
	Unemployed	230	60.5%
Monthly Household Income	Less Than 1800 NIS	135	35.5%
	1800-2700 NIS	98	25.8%
	2700-4000 NIS	74	19.5%
	More Than 4000 NIS	73	19.2%
Do You Live with Your Parents?	Yes	300	78.9%
	No	80	21.1%
Cumulative Average	Less Than 60%	33	8.7%
	60%-69.9%	57	15.0%
	70%-79.9%	163	42.9%
	80%-89.9%	94	24.7%
	90%-99.9%	33	8.7%
Type of the institution	College	238	62.6%
	University	142	37.4%

3. 1. Sources of Stresses

Among the 21 listed stressors, the most frequently reported by students was "Problems with Studies in General" (83.4%), followed by "Financial Difficulties" (81.6%) and "Sleeping Disorders" (78.9%). Other common sources included "Worries About the Future" (75.8%) and "Academic Workload" (67.4%). In contrast, less frequently reported stressors were "Conflicts with Roommates" (42.9%) and "Lack of Parental Support" (42.1%). The highest rates of non-experienced stressors were found in "Problems with Accommodation" (54.5%) and "Conflicts with Roommates" (57.1%), as detailed in **Table 2.**

Table 2: Sources of Stresses (n=385)

Item	Experienced		Not Experienced	
	n	%	n	%
1. Financial Difficulties	310	81.6%	70	18.4%
2. Family Problems	245	64.5%	135	35.5%
3. Sleeping Disorders	300	78.9%	80	21.1%
4. Worries About Future	288	75.8%	92	24.2%
5. Problems with Studies in General	317	83.4%	63	16.6%

6. Stress of Academic Workload	256	67.4%	124	32.6%
7. Trouble with My Parent(S)	201	52.9%	179	47.1%
8. Trouble with My Siblings	180	47.4%	200	52.6%
9. Trouble with My Lecturer(S)	211	55.5%	169	44.5%
10. Trouble with My Course Mates	187	49.2%	193	50.8%
11. Problems with Accommodation	173	45.5%	207	54.5%
12. Problems with Learning Environment	241	63.4%	139	36.6%
13. Conflicts with My Roommate(S)	163	42.9%	217	57.1%
14. Problems Staying Away from Home	192	50.5%	188	49.5%
15. Often Interpersonal Conflicts in School	184	48.4%	196	51.6%
16. Lack of Parental Supports	160	42.1%	220	57.9%
17. Bad News While in School	231	60.8%	149	39.2%
18. Appetite Change	246	64.7%	134	35.3%
19. Transportation Problems	270	71.1%	110	28.9%
20. Problems Getting Life Partner	197	51.8%	183	48.2%
21. Low Self-Esteem	183	48.2%	197	51.8%

3. 2. Levels of Stress among the Students

As shown in **Figure 1**, the pie chart presents the distribution of stress levels among a group of students. A striking 93.4% of the students report experiencing moderate levels of stress, indicating that the majority feel a noticeable but perhaps manageable degree of stress. Notably, a smaller proportion, 5%, report high levels of stress, which suggests a significant impact on their well-being and daily functioning. Only1.6% of the students report low levels of stress, indicating that stress is a common and significant factor for nearly all the students surveyed. The data underscores the prevalence of moderate stress in the student population, with high stress also being a concerning issue for a notable minority.

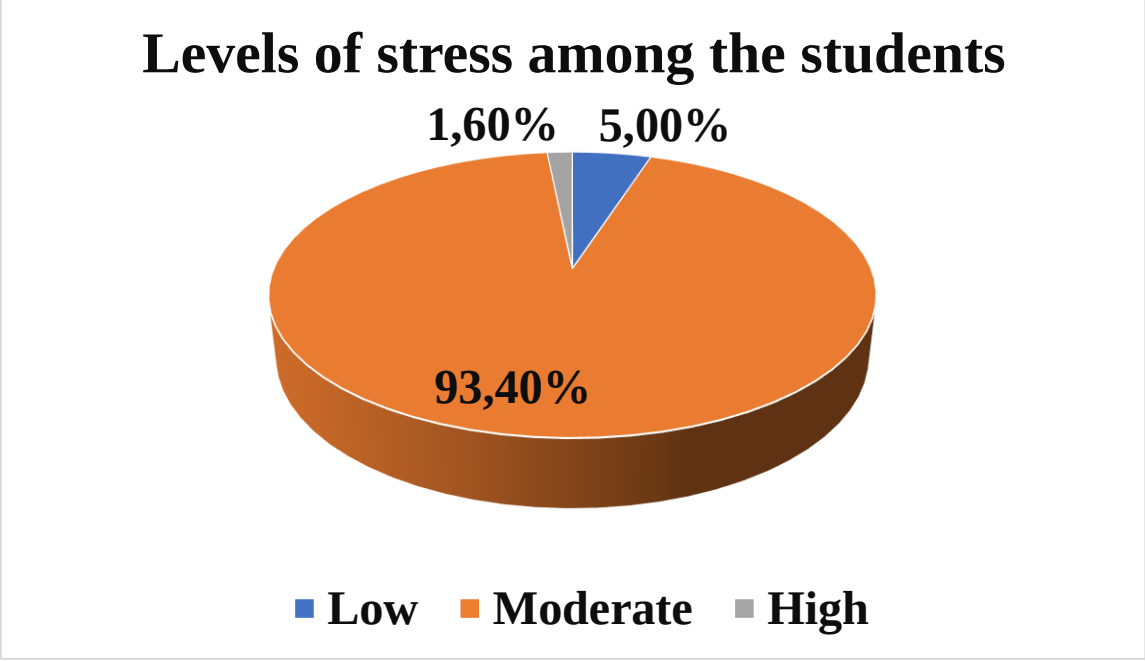

Figure 1. Level of Stress among the participants (n=385)

3. 3. Mean Score for Each Item of the Stress Scale

Among the stress scale items, “Feeling nervous and stressed” (M = 3.30) and “Feeling confident in handling personal problems” (M = 3.21) had the highest mean scores, indicating stronger perceptions of stress. In contrast, items such as “Being

upset due to unexpected events" (M = 2.89), "Being unable to control important things" (M = 2.84), and "Feeling unable to cope" (M = 2.91) showed lower stress perception. Similarly, items related to controlling irritations, feeling on top of things, and handling uncontrollable events had mean scores between 2.81 and 2.95, suggesting they were not commonly perceived as stressors. As shown in **Table3**.

Table 3: Perceived Stress Scale among Participants (n=385)

No.	Item	M	SD	Status
1	Being Upset Due to Unexpected Happenings	2.89	1.295	Not Perceived stress
2	Being Unable to Control Important Things in Your Life	2.84	1.136	Not Perceived stress
3	Feeling Nervous and Stressed	3.30	1.215	Perceived stress
4	Feeling Confident of Your Ability to Handle Personal Problems	3.21	1.201	Perceived stress
5	Feeling That Things Were Going Your Way	2.90	1.171	Not Perceived stress
6	Found Out That You Could Not Cope with All the Things That You Had to Do	2.91	1.125	Not Perceived stress
7	Being Able to Control Irritations in Your Life *	2.95	1.155	Not Perceived stress
8	Feeling That You Were on Top of Things *	2.93	1.142	Not Perceived stress
9	Being Angered Because Of Things That Were Beyond Your Control *	2.81	1.222	Not Perceived stress
10	Feeling That Difficulties Were Piling Up So High That You Could Not Overcome Them *	2.91	1.181	Not Perceived stress
	Total Mean Score (10 items)	**2.96**	**.359**	**Not Perceived stress**

**Reverse coded*

3. 4. Coping Strategies Used among Participants

The most frequently reported coping strategies were self-distraction and acceptance (77.6% each), followed by humour (75.3%) and planning (74.2%). Active coping and positive reframing were also commonly used, reported by 68.7% and 67.6% of participants, respectively.

Emotional support was used by 62.9%, and instrumental support by 54.2%. Denial and self-blame were reported by 49.5% and 60.5%, respectively. Substance use was less common, with 28.2% of participants reporting this strategy. As shown in **Table 4**.

Table 4: Coping Strategies Used among Participants (n=385)

No.	Coping Strategies Used	Yes		No	
1		**n**	**%**	**n**	**%**
2	Self-Distraction	295	77.6%	85	22.4%
3	Active Coping	261	68.7%	119	31.3%
4	Denial	188	49.5%	192	50.5%
5	Substance Use	107	28.2%	273	71.8%
6	Emotional Support Use	239	62.9%	141	37.1%
7	Instrumental Support Use	206	54.2%	174	45.8%
5	Behavioural Disengagement	220	57.9%	160	42.1%
9	Venting	248	65.3%	132	34.7%
10	Positive Reframing	257	67.6%	123	32.4%
11	Planning	282	74.2%	98	25.8%
12	Humour	286	75.3%	94	24.7%
13	Acceptance	295	77.6%	85	22.4%
14	Religion	284	74.7%	96	25.3%
18	Self– Blame	230	60.5%	150	39.5%

Stress levels significantly differed across several demographic variables. Females reported higher stress (M = 3.08, SD = 0.284) than males (M = 2.85, SD = 0.389; $p < .001$). Year of study was also significant ($p = .005$), with first-year students

reporting lower stress. Participants with fathers (p = .001) or mothers (p = .001) with no formal education had lower stress scores compared to those with higher parental education.

Employment status was associated with stress levels (p = .001), with unemployed participants reporting higher stress (M = 3.03, SD = 0.325) than those employed full-time. Cumulative academic average was also significant (p = .001), with higher stress reported among students with lower academic performance.

Table 5: Differences between demographic variables in terms of stress (n=385)

Demographic variable		n	M	SD	P-value
Gender	Male	193	2.85	.389	<.001*
	Female	187	3.08	.284	
Age	18-20 Years Old	167	2.96	.346	.974
	21-23 Years Old	144	2.97	.356	
	24-26 Years Old	34	2.98	.404	
	27 Years Old and Above	35	2.96	.394	
Level of Education	Diploma	126	3.00	.359	.220
	Bachelor's Degree	254	2.95	.358	
Years of the study	First Years	95	2.87	.345	.005*
	Second Years	101	3.00	.321	
	Third Years	64	3.07	.320	
	Fourth Years	120	2.95	.402	
Location of Residence	Major City (e.g., Ramallah, Nablus)	113	2.91	.383	.116
	Town/Village	224	3.00	.325	
	Refugee Camp	43	2.95	.441	
Marital Status	Single	271	2.97	.335	.238
	Married	61	2.94	.373	
	Divorced/Separated	28	2.86	.504	
	Widowed	20	3.06	.376	
Number of Dependents	None	124	2.90	.386	.064
	1-2	188	3.00	.338	
	Or More	68	2.98	.355	
Highest Levels of Education (father)	No Formal Education	111	2.79	.379	.001*
	High School	156	3.08	.299	
	Diploma	35	3.01	.366	
	Bachelor's Degree	60	2.95	.283	
	Master's Degree or Higher	18	2.98	.499	
Highest Levels of Education (mother)	No Formal Education	101	2.85	.373	.001*
	High School	136	3.06	.311	
	Diploma	76	2.93	.384	
	Bachelor's Degree	52	2.95	.314	
	Master's Degree or Higher	15	3.05	.458	
Employment Status (If Applicable)	Employed Fulltime	92	2.84	.377	.001*
	Employed Part-time	58	2.92	.404	
	Unemployed	230	3.03	.325	
Monthly Household Income	Less Than 1800 NIS	135	2.92	.332	.137
	1800-2700ils	98	3.03	.386	
	2700-4000ils	74	2.95	.354	
	More Than 4000ils	73	2.98	.366	
Do You Live with Your Parents?	Yes	300	2.96	.3387	.960
	No	80	2.97	.429	
Cumulative Average	Less Than 60%	33	2.75	.352	.001*
	60%-70%	57	3.03	.272	
	70%-80%	163	2.95	.377	
	80%-90%	94	3.00	.357	
	90%-99.9%	33	3.07	.334	
Type of the Institution	College	238	2.95	.338	.455
	University	142	2.98	.392	

*Independent t test and One-Way ANOVA tests, *Significant at p=<0.05.*

4. Discussion

The results of this study provide valuable insights into the stress levels, sources of stress, and coping strategies among nursing students in the West Bank. They highlight the psychological challenges these students face, shaped by academic demands, socio-economic conditions, and cultural aspects. These conclusions indicate a clear need for interventions and support for nursing students with the ability to minimize stress and promote overall well-being throughout their education.

4. 1. Stress Levels among Nursing Students

The study found that just 5% of students reported high stress and 1.6% reported low stress, while the vast majority (93.4%) reported moderate stress. The average item score on the PSS-10 was 2.96, placing it within the standardized moderate stress category (2.34–3.67). It is noteworthy that, while the scores of individual items were somewhat mild, the aggregate impact indicated sustained— that is, moderate— stress (Al-Gamal et al., 2018; Xu et al., 2023). The mean score of 2.96, although moderately stressful, lies closer to high-stress than it does low-stress in the moderate category. These results align with other studies that emphasize nursing students as a group at risk for stress because of clinical exposure, coursework, and emotional labor (Gibbons et al., 2011; Seyedfatemi et al., 2007). The high prevalence of moderate stress indicates that although most students are coping, ongoing pressures on their well-being necessitate proactive support mechanisms (Pulido-Martos et al., 2012). Remarkably, the sample is at the top end of the moderate range with an overall mean score of 2.96 on the PSS- 10. The socio-political complexity of living and studying on the West Bank is likely to make students' stress even more severe, even if they may not perceive individual stressors as overwhelming on their own (Salameh et al., 2025).

4. 2. Common Sources of Stress

Academic pressures were among the most commonly cited, with 81.6% reporting money difficulties and 83.4% indicating general study issues. These results are consistent with earlier research by Pulido-Martos et al. (2012) and Bolarinwa et al. (2023), which found that financial limitations and academic pressure were the main sources of stress in nursing education. The prevalence of sleep issues and future-focused concerns suggests that stress impacts students' everyday functioning and mental health outside of the classroom (Alsaqri, 2017; Sharif & Masoumi, 2005).

The high rate of stress associated with financial difficulties and future uncertainty highlights the region's larger socioeconomic problems (Chaabane et al., 2021). Conversely, interpersonal stresses, including disagreements between roommates and a lack of parental support, were less commonly mentioned, indicating that although social obstacles do exist, they could be subordinated to financial and scholastic issues in this way (Loureiro et al., 2024).

4. 3. Coping Strategies Used

The adaptive coping methods that the participants preferred were humour (75.3%), acceptance (77.6%), self-distraction (77.6%), and planning (74.2%). These strategies are an attempt to keep emotional equilibrium and control when dealing with continuous stress (Carver et al., 1989). Plans and humour are in line with research by Carver et al. (1989), which highlighted the need for systematic problem-solving and positive reframing in stress management.

As a positive measure of students' resilience and understanding of better coping techniques, maladaptive tactics including drug use (28.2%) and denial (49.5%) were less frequently reported (Lazarus & Folkman, 1984). But, given that it might eventually result in internalised misery and lowered self-esteem, the comparatively high utilisation of self-blame (60.5%) is cause for worry (Reeve et al., 2013; Seyedfatemi et al., 2007).

4. 4. Differences in Stress by Demographic Variables

There were notable variations in stress levels according to gender, academic year, parental education, work status, and cumulative average. In line with international studies showing that women frequently report higher levels of perceived stress due to both social and biological causes, female students reported higher stress levels than male students (Hamaideh et al., 2024; Reeve et al., 2013).

Students in their second and third yearsreported higher stress levels, likely due to tougher classes and more clinical work (Jimenez et al., 2010). In contrast, fourth-year nursing students reported lower stress levels compared to their second- and third-year peers, possibly due to adaptation over time. As students progress through the nursing program, they may gradually develop greater psychological resilience, improved time-management skills, and stronger coping mechanisms for handling academic and clinical demands. Additionally, the anticipation of graduation may foster a sense of purpose and motivation that helps buffer stress (Al-Gamal et al., 2018).

Additionally, students with well-educated parents often feel more stress, possibly because they feel pressured to achieve high grades (Li et al., 2024). Students with poorer academic averages and those without jobs also reported much greater levels of stress, indicating a connection between mental health and academic and economic instability (Bolarinwa & Ishola, 2023).

4. 5. Study Limitations

This study offers useful insights into the stress and coping strategies used by nursing students in the West Bank, but it has some limitations. One major issue is its cross-sectional design. This means the study only examines data at a single point in time, which makes it challenging to understand if and how specific stress factors directly impact students' ability to cope with stress or influence their academic performance (Polit & Beck, 2008). To monitor changes in stress over time, a longitudinal study would be more appropriate.

Second, self-reported questionnaires were used to obtain the data, which might lead to response bias. According to Tourangeau and Yan (2007), participants may exaggerate their usage of constructive coping mechanisms or underreport activities deemed socially unacceptable, such as substance abuse. Furthermore, mood at the moment of reaction might affect emotional subjects like stress (Tourangeau & Yan, 2007).

Third, this study included only students from institutions based in the West Bank, which limits comparative generalisability with regard to other geographic or political regions. The unique political climate, ongoing conflict, and movement restrictions in the West Bank create a highly specific environment that may not reflect the experiences of nursing students in more stable or differently structured settings. Additionally, variations between public and private institutions within the West Bank were not examined, despite possible differences in curriculum intensity, access to resources, clinical placement quality, and psychosocial support services. These institutional differences could significantly influence students' stress levels and coping mechanisms. Therefore, future research should include larger and more diverse samples, incorporating participants from multiple geographic areas.

Lastly, although the instruments have been standardised, it is possible that language and culture may affect how participants interpreted certain items on the stress and coping scales. In this study the questionnaire was disseminated in Arabic; however, the cultural concepts and meanings associated with stress, emotional expression, and coping, as described in the scale constructs, may not have fully captured the culturally specific meanings that emerged. So, future research should seek to use culturally adapted instruments or mixed methods to attain more meaningfully constrained enquiries from their context.

4. 6. Implications of the Study

The study's conclusions have significant implications for institutional policy, nursing education, and student mental health. First of all, stresses are clearly multifaceted, including anything from financial instability and future uncertainty to academic pressure. For pupils in underprivileged or high-risk groups in particular, interventions must be tailored to the individual and subject-specific (Bolarinwa & Ishola, 2023).

Secondly, this study shows that financial strain has consequences on students' emotional and cognitive health and is a persistent burden. In order to ease this burden, post-secondary institutions should consider implementing initiatives for financial literacy programming, scholarships, and part-time work (Pulido-Martos et al., 2012).

Thirdly, to address the range of both adaptive and maladaptive coping behaviours identified in this study, universities must address 'the gaps' by implementing programs that build resilience. 'The gaps' could include semester-long mental health education series, elective courses on stress management, and peer support groups. Additionally, counselling centres should reach out to students and build rapport and connection so nurses would know who to access. Orientation programs need to emphasise the same connections and outreach for engagement but also utilise electronic and multimodal options so that students are familiar and accustomed to seeking support once they identify or recognise the need for help.

When institutions implement this staged and systematic approach, they can not only ease immediate stressors but also develop both a culture of long-term, sustained psychological well-being and academic success for nursing students.

4. 7. Recommendations for Future Research and Practice

To capture stress patterns throughout students' academic experiences, future studies may consider using longitudinal research designs. This would help identify the causes and timing of periods of high stress and strategies that evolve over time.

Moreover, richer stories of students' lived experiences of stress can become exposed through qualitative research methodologies, such as focus groups and in-depth interviews, which typically remain hidden in quantitative surveys. These methods can uncover intricate patterns of stress guided by gender, social roles, and family expectations.

Evaluations of evidence-based interventions are also urgently needed. Universities ought to test and evaluate peer mentorship, financial counselling, and resilience training initiatives to see how they affect student outcomes like GPA, retention, and mental health.

Lastly, institutional integration should be the goal of policy initiatives, where social, psychological, and academic support services work together to provide all-encompassing programs for students' well-being. By cultivating this kind of collaboration, academic institutions may establish a more welcoming and encouraging atmosphere that promotes education and individual development.

5. Conclusion

The findings of this study highlight the importance of considering the academic level, gender, and socioeconomic status of nursing students when developing interventions. Institutions should be able to improve the well-being of students through resilience workshops, more financial aid funding, and access to mental health services. The study identifies three essential recommendations: (1) stress management programs, (2) targeted financial assistance, and (3) counselling outreach. The proposed recommendations could start an extended process that aims to build nursing students' psychological resilience that will ultimately lead to their success as students in the West Bank and equivalent areas.

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Data Availability

No data was used for the research described in the article.

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