ISSN: 2349-6495(P) | 2456-1908 (O)

International Journal of Advanced Engineering Research and Science

(IJAERS)

An Open Access Peer-Reviewed International Journal

Journal DOI: 10.22161/ijaers

Issue DOI: 10.22161/ijaers.1210

AI PUBLICATIONS

Vol.- 12 | Issue - 10 | Oct 2025

editor.ijaers@gmail.com | editor@ijaers.com | https://www.ijaers.com/

International Journal of Advanced Engineering Research and Science

(IJAERS)

(ISSN: 2349-6495(P)| 2456-1908(O))

DOI: 10.22161/ijaers

Vol-12, Issue-10

October, 2025

Publisher

AI Publication

Email: editor.ijaers@gmail.com; editor@ijaers.com

Web: www.ijaers.com

Vol-12, Issue-10, October 2025

(10.22161/ijaers.1210)

Detail with DOI (CrossRef)

International Journal of Advanced Engineering Research and Science (IJAERS)
Peer-Reviewed Journal
ISSN: 2349-6495(P) | 2456-1908(O)
Vol-12, Issue-10; Oct, 2025
Journal Home Page Available: *https://ijaers.com/*
Article DOI: *https://dx.doi.org/10.22161/ijaers.1210.1*

Advances in Nanoplatform Design and Theranostics for HNC via the Tumor Microenvironment

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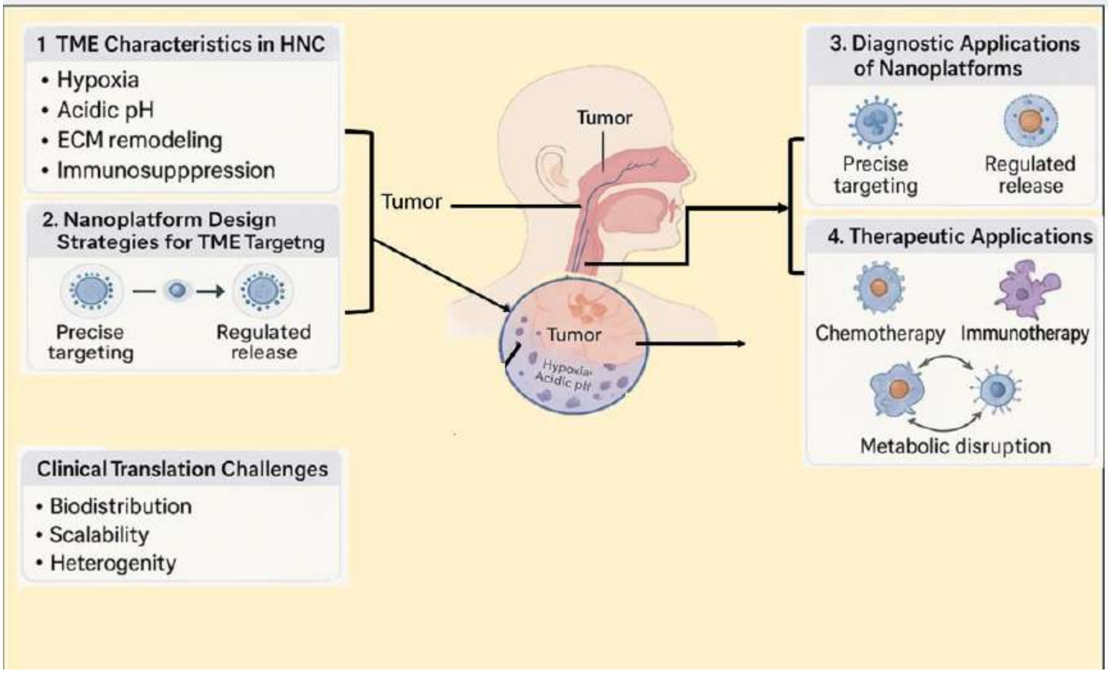
Received: 25 Aug 2025,
Received in revised form: 23 Sep 2025,
Accepted: 27 Sep 2025,
Available online: 07 Oct 2025

Keywords— Head and neck cancer; Tumor microenvironment; Nanoplatform; Nanotheranostics; Imaging; Targeted therapy.

Abstract— *Head and neck cancer (HNC) accounts for approximately 930,000 new cases and 470,000 deaths annually, with squamous cell carcinoma (HNSCC) of the upper aerodigestive tract representing the dominant histology. Tobacco use, alcohol consumption and high-risk human papillomavirus infection are the principal risk factors. Standard-of-care modalities such as surgery, radiotherapy, chemotherapy and photodynamic therapy frequently fail in advanced disease because of off-target toxicity and inherent or acquired resistance. Recent insights into the tumor microenvironment (TME) characterized by hypoxia, acidic pH, extracellular-matrix remodeling and immunosuppression have revealed actionable therapeutic targets. This review synthesizes how nanotechnology exploits these TME features to enhance HNC diagnosis and treatment. We first delineate the unique TME landscape of HNSCC and then classify TME-responsive nanoplatforms according to their design principles: pH, redox, enzyme or hypoxia-triggered release; active targeting of overexpressed receptors; and multimodal theranostics. Subsequent sections evaluate diagnostic applications (MRI, CT, PET, optical and molecular imaging) and therapeutic strategies, including chemotherapy delivery, immunomodulation and combination regimens. Finally, we address translational bottlenecks biocompatibility, manufacturing scalability, tumor heterogeneity, regulatory complexity and propose precision-nanomedicine solutions. Pre-clinical studies demonstrate that TME-activated nanoplatforms achieve superior tumor accumulation, reduced systemic toxicity and integrated imaging-therapy functions. Multifunctional nanocarriers that co-load chemotherapeutics, photosensitizers and immune checkpoint inhibitors further exhibit synergistic anti-tumor activity. Although challenges related to biodistribution, batch-to-batch* *reproducibility and patient stratification persist. Interdisciplinary efforts spanning materials science, oncology and regulatory science are poised to accelerate the clinical translation of TME-focused nanotheranostics toward individualized HNC management.*

Graphical abstract



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I. INTRODUCTION

Head and neck cancer (HNC) is the seventh most common malignancy worldwide, encompassing tumors of the larynx, pharynx and oral cavity [1]. Each year it accounts for approximately 930,000 new cases and 470,000 deaths [2]. Roughly 90% of these lesions are mucosal squamous cell carcinomas (HNSCC) [3]. Major risk factors include tobacco use, alcohol consumption and high-risk human papillomavirus infection; the latter is particularly relevant to oropharyngeal tumors. Despite therapeutic advances, five-year survival for advanced HNSCC remains below 50% [3].

Standard-of-care modalities such as surgery, radiotherapy, chemotherapy and photodynamic therapy [4] are limited by systemic toxicity and off-target effects [5]. Late diagnosis, intrinsic resistance and post-treatment relapse further compromise efficacy [5]. Cisplatin-based regimens, for example, frequently induce nephrotoxicity and ototoxicity [6]. These shortcomings have intensified interest in tumor targeted nanotechnologies. Engineered nanoparticles offer tumor specific delivery, multimodal therapy and reduced systemic exposure [7]. Recent advances include TME-responsive bio-nanocomposites that exploit microenvironmental cues for precision treatment.

Head and neck TME is a highly heterogeneous ecosystem composed of malignant cells, cancer-associated fibroblasts, immune infiltrates, a leaky vasculature and a dense extracellular matrix [8]. Bidirectional crosstalk continuously reshapes this milieu: hypoxic tumor cells up-regulate pro-invasive stromal genes, while CAFs secrete cytokines and matrix proteins that facilitate invasion [9].

Nanotechnology provides versatile solutions [10]. Stimuli responsive platforms achieve tumor specific drug release by exploiting pH sensitive linkers, redox labile bonds or enzyme cleavable matrices [11]. Functional additives such as photosensitizers, metallic or magnetic cores, further enable imaging and combinatorial therapy [12]. Surface functionalization (EGFR ligands, folate) mediates active targeting, whereas the EPR effect drives passive accumulation [13]. Multifunctional architectures can co-deliver chemotherapeutics, immunomodulators and imaging agents while navigating biological barriers such as abnormal vessels or dense ECM [14].

Here, we review the state-of-the-art in TME-responsive nanoplatforms for HNC. We first dissect the unique features of the HNC-TME, then classify design strategies that respond to pH, redox, enzymatic activity or hypoxia. Subsequent sections evaluate diagnostic applications (molecular assays and advanced imaging) and therapeutic interventions (chemotherapy, immunotherapy and combination regimens). Finally, we outline translational challenges and future directions. By integrating materials science with tumor biology, TME-activated nanoplatforms promise to transform HNC theranostics.

II. CHARACTERISTICS OF THE TUMOR MICROENVIRONMENT IN HEAD AND NECK CANCER

The tumor microenvironment (TME) of head and neck cancer (HNC) is a multicellular and multifactorial ecosystem that orchestrates tumor growth, invasion and metastasis (Fig. 1) [15]. Although conventional therapies have traditionally targeted malignant cells, accumulating evidence indicates that stromal, immune and extracellular components critically modulate therapeutic efficacy [15]. Head and neck squamous cell carcinoma (HNSCC), which accounts for the vast majority of HNC, displays a heterogeneous TME composed of cancer cells, cancer-associated fibroblasts (CAFs), immune infiltrates and an abundant extracellular matrix (ECM) (Fig. 1) [16]. Single-cell RNA-sequencing studies have revealed pronounced transcriptional, developmental, metabolic and functional heterogeneity among these populations [17]. Consequently, the TME constitutes both a barrier to conventional therapy and an attractive target for next-generation nanomedicine [18].

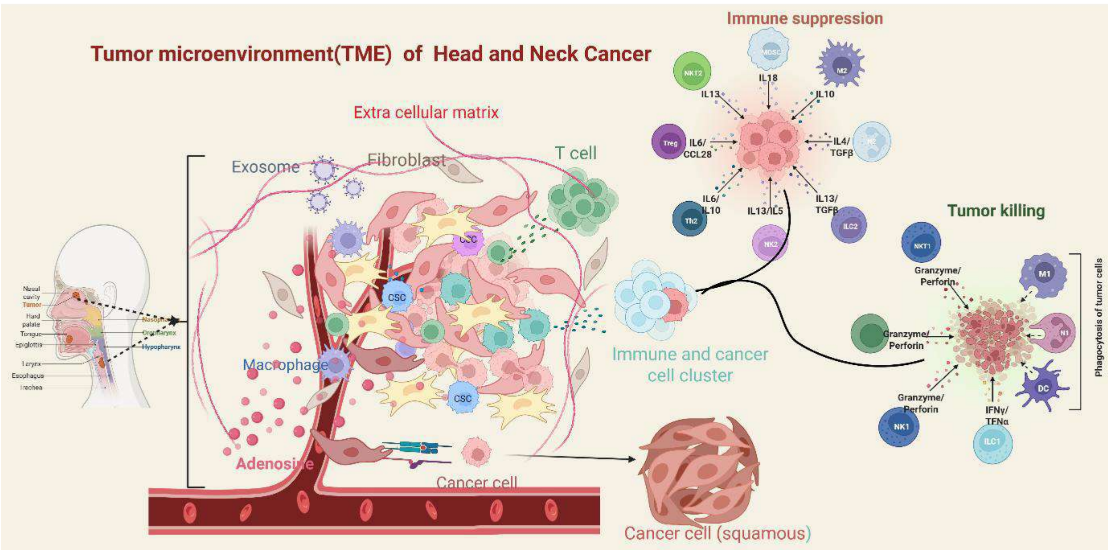

Fig.1 Cross section of Tumor Microenvironment (TME) in Head and Neck Cancer @BioRender.com

Immunosuppressive infiltrates

HNSCC lesions are densely infiltrated by regulatory T cells (Tregs), myeloid-derived suppressor cells (MDSCs) and tumor-associated macrophages (TAMs) [19]. These populations express checkpoint ligands (e.g., PD-L1) and secrete inhibitory cytokines such as TGF-β and IL-10, thereby attenuating cytotoxic T-cell activity [20]. Under hypoxia, HIF-1α up-regulation further amplifies PD-L1 expression, enhances EGFR signaling and promotes vascular abnormalities, collectively skewing the microenvironment toward immune tolerance [21].

Aberrant angiogenesis and hypoxia

Neo-angiogenesis in HNSCC is rapid yet chaotic, producing tortuous, hyperpermeable vessels that generate heterogeneous perfusion and widespread hypoxia [22]. Tumor hypoxia is an independent predictor of poor prognosis and is associated with aggressive behavior, chemo and radio-resistance and inferior clinical outcomes [23], [24]. In addition, hypoxia reinforces immunosuppression by recruiting Tregs and MDSCs, thereby complicating therapeutic interventions [24].

Extracellular matrix remodeling

The HNSCC ECM is enriched in collagen, fibronectin and proteoglycans [25]. CAFs and cancer cells continuously remodel this matrix: collagen becomes hyper-cross-linked and fibers align, increasing tissue stiffness (Fig. 2) [25]. Overexpressed matrix metalloproteinases (MMP-2, MMP-9) degrade basement-membrane components, facilitating invasion and metastasis [26]. Paradoxically, the same dense matrix impedes drug diffusion, causing therapeutic agents to become entrapped within the stroma [27].

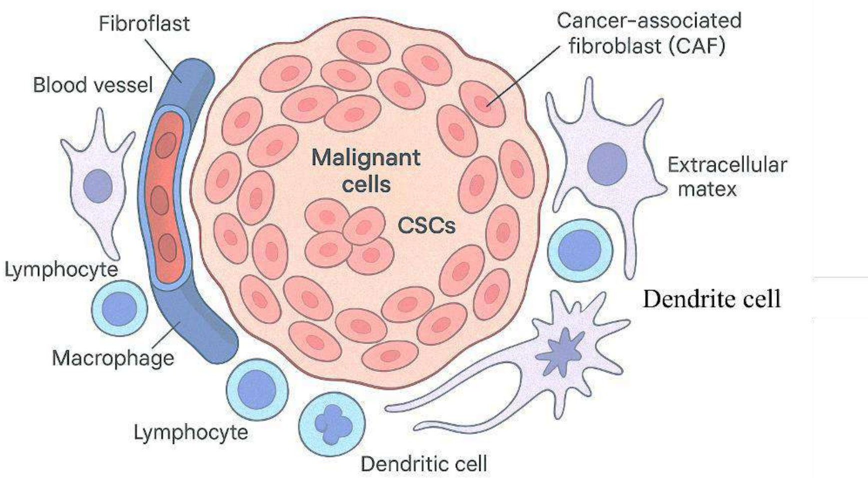

Fig. 2 Cellular components in TME @BioRender.com

Chronic inflammation

Chronic inflammation driven by tobacco, alcohol, viral infections or tissue trauma is a hallmark of HNSCC [28]. Infiltrating neutrophils, macrophages and other myeloid cells release IL-6, IL-8, TNF-α and macrophage migration inhibitory factor (MIF), which promote angiogenesis, epithelial mesenchymal transition (EMT) and immune evasion [29]. These cytokines also recruit additional suppressive immune cells and remodel the ECM, thereby establishing a self-perpetuating inflammatory niche that sustains tumor progression [29].

III. DESIGN STRATEGIES OF NANOPLATFORMS BASED ON THE TUMOR MICROENVIRONMENT

Recent advances in nanomedicine have generated a diverse arsenal of platforms for head and neck cancer (HNC) (Fig. 3) [30]. These systems can be broadly categorized as metallic, lipid-based, polymeric or inorganic, each engineered to exploit unique features of the tumor microenvironment (TME).

Metallic and inorganic nanosystems

Gold nanoparticles (Au NPs) serve dual roles: upon near-infrared (NIR) irradiation they mediate photothermal therapy (PTT) [31], [32], while their high atomic number enhances radiotherapy via secondary-electron emission [33]. Iron oxide nanoparticles (Fe_3O_4) provide magnetic-hyperthermia and magnetically guided drug delivery [34]. Cerium oxide (CeO_2) NPs protect normal tissues from radiation-induced oxidative injury yet sensitize tumor cells through redox modulation [35]. Gadolinium (Gd) and silver (Ag) NPs generate reactive oxygen species (ROS) to potentiate radiation and induce apoptosis [36], [37]. Gd NPs additionally benefit from low intrinsic toxicity, renal clearance and preferential tumor accumulation via the EPR effect [38].

Lipid-based nanocarriers

Liposomes and nanomicelles possess a phospholipid architecture that simultaneously accommodates hydrophilic and hydrophobic payloads [39]. Surface PEGylation and active ligands (e.g., anti-EGFR antibodies) prolong circulation and enhance tumor specificity [40], [41]. Clinically, liposomal cisplatin has improved pharmacokinetics and reduced nephrotoxicity in HNC patients [42].

Polymeric and solid-lipid platforms

Poly(lactic-co-glycolic acid) (PLGA) and chitosan NPs offer controlled-release kinetics and excellent biocompatibility [43]. Solid-lipid nanoparticles (SLNPs, 50–1000 nm) encapsulate both hydrophilic and lipophilic drugs within a solid-lipid core, shielding them from degradation and minimizing systemic exposure [44], [45]. Incorporating liquid lipids into the matrix increases drug loading by creating lattice imperfections [46]; SLNPs loaded with andrographolide, for instance, enhance anti-HNC efficacy at reduced doses [47].

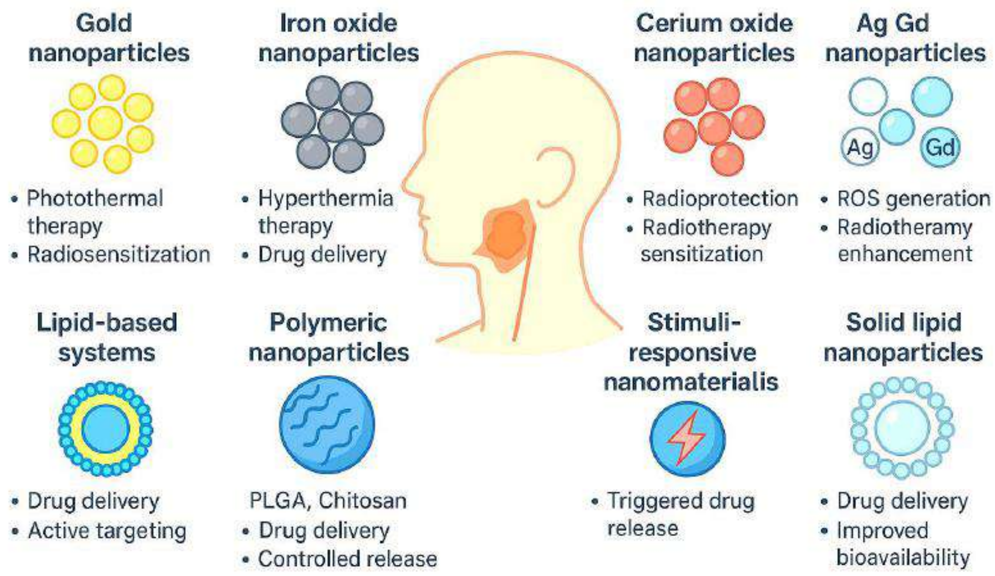

Fig.3 Nanoparticle advancements in contemporary HNC treatment @BioRender.com

Mesoporous silica nanoparticles (MSNPs)

MSNPs possess FDA-recognized safety, uniform pore sizes (2-23 nm) and high loading capacity [48]. Surface functionalization enables siRNA or drug co-delivery, pH/redox-responsive release and immune evasion [49]. A single MSNP can simultaneously carry doxorubicin and MDR1-siRNA to overcome chemoresistance while lowering cardiotoxicity [50].

Stimuli-responsive "smart" systems

Third and fourth generation nanocarriers exploit intrinsic TME cues or external triggers for on-demand drug release [51], [52]. pH-sensitive polymers or acid-labile linkers (e.g., hydrazone) disintegrate in the acidic extracellular milieu. Redox-responsive carriers containing disulfide bonds rupture under high intracellular glutathione levels [53]. Enzyme-cleavable coatings (MMP- or hyaluronidase-sensitive) fragment upon contact with overexpressed proteases. Hypoxia-activated prodrugs (nitroimidazoles, quinones) are reduced only under ≤2 % O_2, generating cytotoxic radicals while sparing normal tissue [54]. Combinatorial triggers (e.g., pH + redox) can be integrated for even stricter spatiotemporal control.

Immune-regulating nanoplatforms

Nanoparticles can deliver or modulate immunomodulators directly within the TME. Checkpoint blockade: anti-PD-L1-decorated NPs restore exhausted T cells [55]. TAM/Treg reprogramming: mannose- or folate-coated NPs deliver CSF-1R inhibitors or siRNA to suppress Tregs and M2-like TAMs. Vaccination: antigen/adjuvant-loaded NPs traffic to lymph nodes, inducing dendritic-cell maturation and cytotoxic T-cell priming. Microenvironment remodeling: $CaCO_3$ NPs neutralize lactic acidosis, while collagenase-loaded NPs degrade dense ECM to enhance immune cell infiltration.

Multifunctional theranostic nanosystems

Advanced platforms integrate therapy and imaging within a single vector. Gold or Gd NPs provide CT/MRI contrast, whereas superparamagnetic iron oxide enables real-time MRI tracking [56]. Composite nanosystems can co-deliver chemotherapeutics, photosensitizers and photothermal agents for triple-combination therapy (chemotherapy + PDT + PTT), as demonstrated with graphene oxide/doxorubicin/protoporphyrin IX nanocomposites. Such theranostic strategies enable image-guided, on-demand therapy and hold promise for precision oncology.

IV. APPLICATIONS OF NANOPLATFORMS BASED ON THE TME IN DIAGNOSIS

4.1 Imaging Diagnosis

Nanoplatforms endow conventional imaging modalities with higher sensitivity, specificity and molecular information.

Magnetic Resonance Imaging (MRI)

Gadolinium-based nanocrystals and superparamagnetic iron oxide nanoparticles (SPIONs) shorten T_1 or T_2 relaxation times and preferentially accumulate in tumors via the EPR effect. Ultra-small $NaGdF_4$ nanocrystals coated with MnO_2 have enabled T_1-weighted hypoxia mapping in HNSCC xenografts [57]. Although still pre-clinical, these agents outperform conventional gadolinium chelates in both relaxivity and targeting specificity.

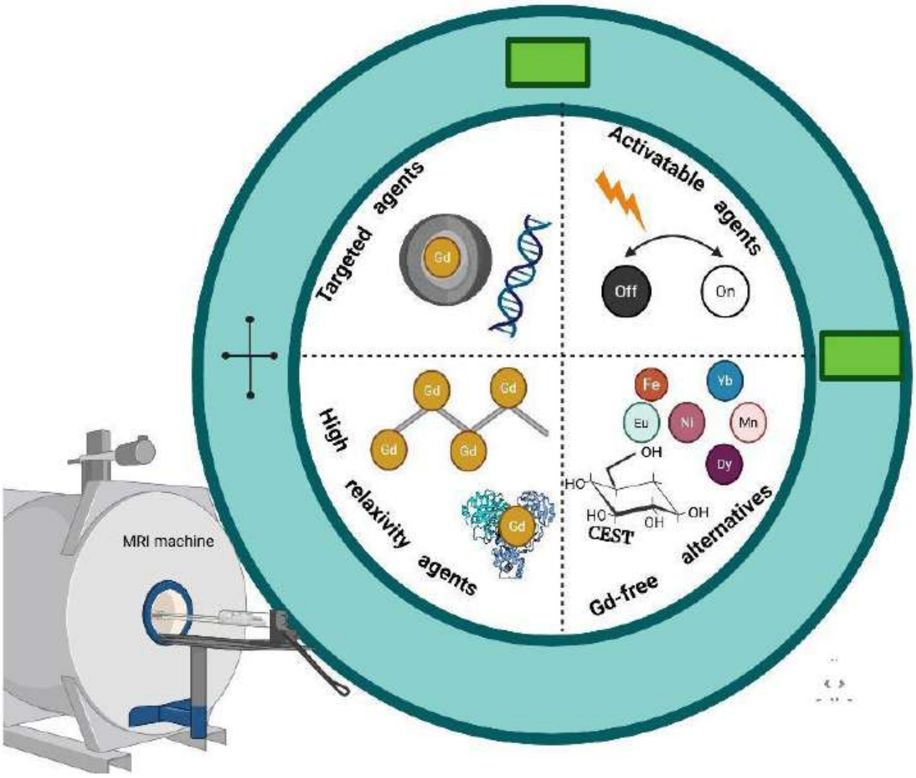

Fig.4 Magnetic Resonance Imaging (MRI) @BioRender.com

Computed Tomography (CT)

High-atomic-number nanoparticles-gold or bismuth-strongly attenuate X-rays, permitting micro-CT visualization of sub-centimetre HNSCC lesions. Antibody- or peptide-conjugated gold nanoprobes have illuminated occult tumors that were invisible with iodinated contrast [58]. Ongoing work is refining ligand density and renal clearance profiles for clinical translation.

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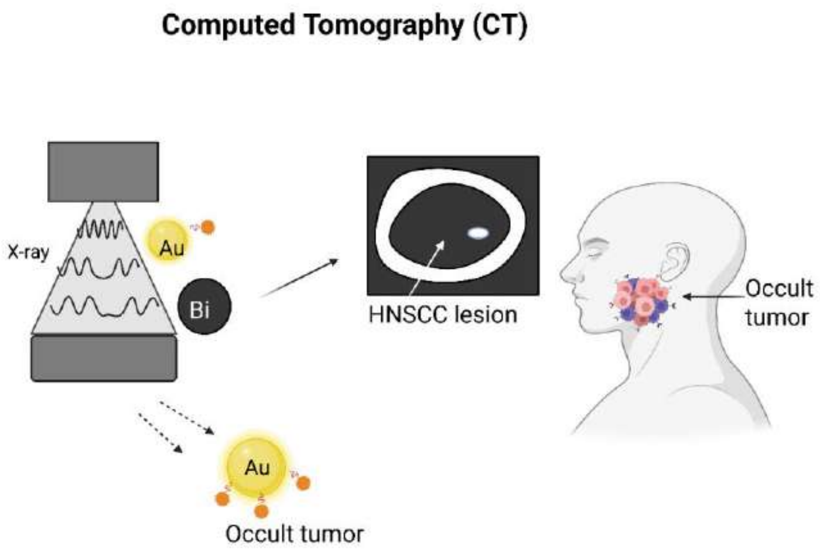

Fig 5. Computed Tomography (CT) @BioRender.com

Positron Emission Tomography (PET)

Radiolabeling nanocarriers with ^{18}F, ^{64}Cu or ^{68}Ga merges the pharmacokinetic advantages of nanoparticles with PET's picomolar sensitivity [59]. Radiolabeled liposomes and polymeric NPs have been used to quantify drug delivery to primary tumors and to detect lymph-node micrometastases [60], [61]. Such nanotracers may soon guide individualized staging and adaptive therapy planning.

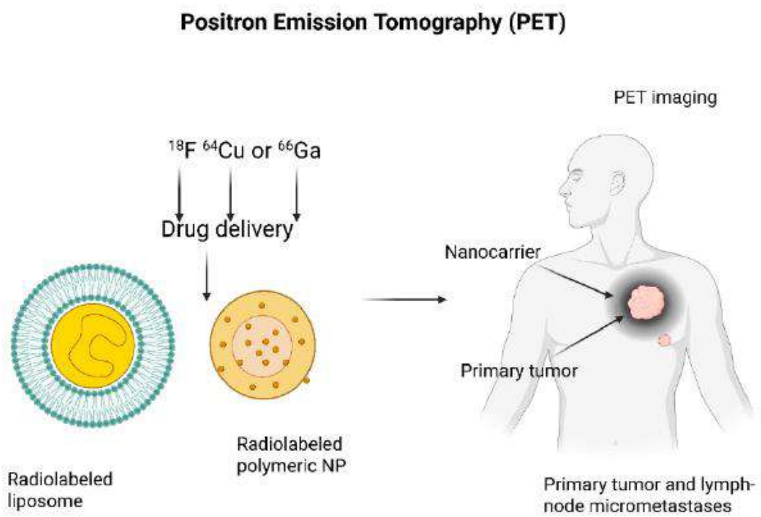

Fig. 6 Position Emission Tomography (PET) @BioRender.com

4.2 Optical Imaging

Fluorescence Imaging

Quantum dots, upconversion nanocrystals and dye-loaded polymer NPs provide NIR fluorescence that delineates tumor margins intra-operatively. pH-activatable nanoprobes that "light up" only in acidic TME further improve signal-to-background ratios [62].

Photoacoustic Imaging (PAI)

Gold nanorods, carbon nanotubes and MnO_2-coated nanocrystals absorb NIR light and generate ultrasound waves, yielding high-resolution, non-ionizing images. Hybrid $NaGdF_4@MnO_2$ probes have simultaneously mapped hypoxia by PAI and MRI in HNC models [63].

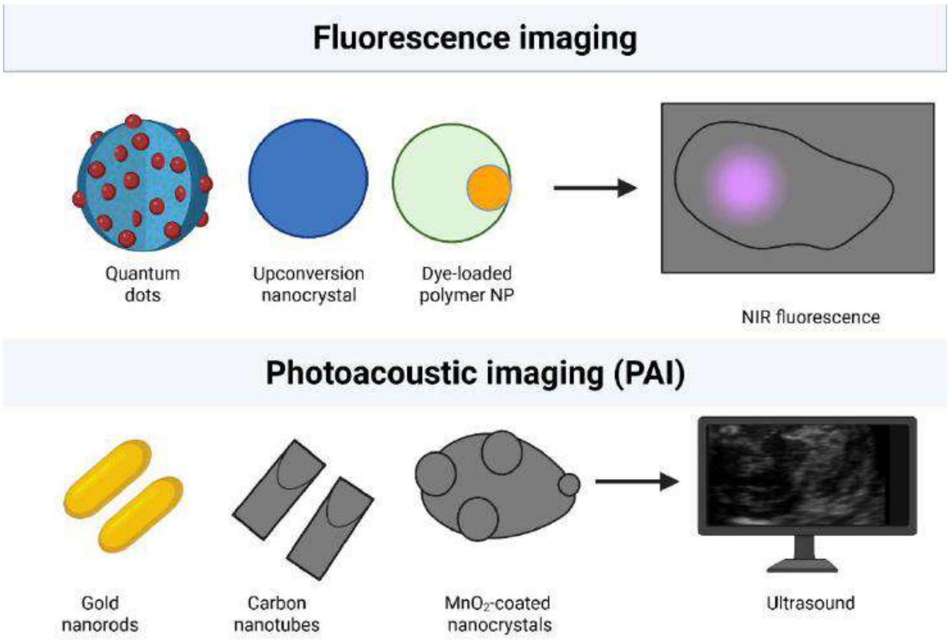

Fig. 7 Fluorescence Imaging and Photoacoustic Imaging (PAI) @BioRender.com

4.3 Molecular Diagnosis

Biomarker Detection

Gold or copper-oxide nanosensors functionalized with antibodies or aptamers enable femtomolar detection of salivary IL-6, IL-8 and TNF-α-established oral cancer biomarkers [64]. Colorimetric or electrochemical readouts facilitate point-of-care screening.

Genomic Testing

Nanoparticle-augmented PCR, isothermal amplification and nanopore sequencing achieve attomolar sensitivity for circulating tumor DNA (ctDNA). Gold nanocluster probes, for example, have detected single-exon deletions in BRCA1 [65]; analogous strategies are being adapted for TP53 or PIK3CA mutations in HNC [66].

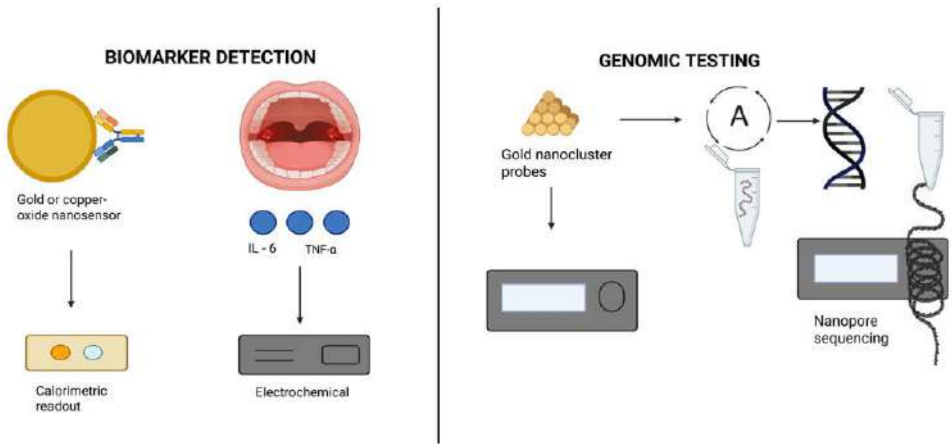

Fig. 8 Biomarker Detection and Genomic Testing @BioRender.com

V. APPLICATIONS OF NANOPLATFORMS BASED ON THE TME IN HNC THERAPY

5.1 Chemotherapy Delivery

Encapsulating cytotoxic agents in liposomes, polymeric micelles or dendrimers increases tumor exposure while sparing healthy tissue. Stimuli-responsive carriers release doxorubicin or paclitaxel preferentially within the acidic, enzyme-rich TME, achieving superior growth inhibition in HNSCC xenografts with fewer systemic side effects. Active targeting via folate, anti-EGFR antibodies or RGD peptides further concentrates the payload at the lesion [67]. Early-phase trials of pegylated liposomal cisplatin and albumin-bound paclitaxel already report improved tolerability in recurrent/metastatic HNC.

5.2 Immunotherapy

Nanoparticles are transforming how immunomodulators reach the tumor:

Checkpoint blockade. Conjugating anti-PD-L1 to polymeric NPs confines antibody activity to the TME, lowering off-target autoimmunity while boosting intratumoral drug levels.

Cytokine delivery. IL-12-loaded lipid nanogels activate local CD8+ T cells without the vascular-leak syndrome seen with free cytokine [68].

Neo-antigen vaccination. PLGA particles co-encapsulating tumor lysates and TLR agonists generate robust, antigen-specific T-cell responses in murine HNSCC.

Microenvironment reprogramming. Acid-neutralizing $CaCO_3$ NPs or collagenase-armed carriers dismantle physical and chemical barriers, enhancing T-cell infiltration and synergizing with adoptive cell therapy.

5.3 Combination & Multimodal Therapy

A single nanocarrier can synchronize chemotherapy, phototherapy and immunotherapy to attack resistant HNC on multiple fronts.

Chemo-phototherapy. Graphene oxide co-loaded with doxorubicin and a photosensitizer eradicates orthotopic tumors under NIR irradiation, overcoming drug efflux [69].

Chemo-immuno. Cisplatin plus a TLR7 agonist delivered in one liposome simultaneously debulks the lesion and licenses dendritic cells, tripling median survival in mice.

Radiosensitization. Intravenously injected gold NPs increase the local radiation dose by ~200%, shrinking hypoxic HNSCC tumors without additional systemic toxicity [70]

Tri-modal platforms. A single hybrid nanocomposite combining cisplatin, a photothermal agent and a PD-L1 siRNA achieved near-complete regression in 80% of animals, whereas any monotherapy failed [71]. Coordinating pharmacokinetics through a unified vector remains a unique advantage of nanomedicine.

VI. CHALLENGES AND PROSPECTS FOR CLINICAL TRANSLATION

6.1 Translational Hurdles

Biocompatibility & Toxicity

Although lipids and FDA-approved polymers are generally safe, residual surfactants, heavy-metal dopants or surface functional groups can trigger complement activation or anti-PEG antibodies [72]. Quantum dots, iron oxides and some up-conversion cores raise additional concerns about renal versus hepatic clearance and potential long-term accumulation in reticuloendothelial organs [73]. Rigorous GLP toxicology in large-animal models (>6 months) and quantitative whole-body autoradiography are now considered essential to map organ distribution and establish no-observed-adverse-effect levels (NOAEL) [74]

Manufacturing & Scalability

Microfluidic or flash-nanoprecipitation methods can narrow size distributions below 10% CV at millilitre scale, yet scale-up to 10-100L batches often compromises morphology and surface ligand density [75]. Hybrid architectures-magnetic core + polymer shell + targeting ligand-require orthogonal conjugation chemistry that is sensitive to pH, ionic strength and shear stress. Continuous-flow manufacturing with in-line PAT (process-analytical technology) is emerging as a GMP-compliant route to maintain batch-to-batch reproducibility [76].

Tumor Heterogeneity

Inter-patient variability in EPR magnitude (2-fold to 10-fold) and receptor expression (EGFR 3–200-fold) means a nanoplatform optimised in one xenograft may underperform in another. Integrating pre-treatment PET/MR imaging or single-cell RNA-seq to stratify patients for high-EPR or high-receptor phenotypes is now being piloted as an adaptive inclusion criterion [77], [78].

TME-Induced Resistance

Dense collagen (>10 mg mL^{-1}) and elevated interstitial fluid pressure (>20 mm Hg) can reduce NP penetration by >80%. Hypoxia-driven HIF-1α signalling further up-regulates ABC transporters and DNA-repair enzymes, counteracting both drug and radiation effects [79]. Combination strategies-co-delivery of ECM-degrading enzymes or HIF-1α inhibitors-are therefore being explored to restore NP diffusion and sensitize resistant cells [80].

Immune Clearance

PEGylation extends circulation half-life from minutes to hours, yet repeated dosing elicits anti-PEG IgM, accelerating blood-clearance (ABC) by 3-5-fold [81]. Zwitterionic polymers, CD47-mimetic peptides or erythrocyte-membrane cloaking are under evaluation to evade opsonization while retaining targeting specificity [82].

Regulatory & Economic Barriers

Multifunctional nanotheranostics occupy a regulatory grey zone spanning drugs, devices and biologics [83]. Each additional modality (imaging agent + drug + ligand) multiplies CMC (chemistry-manufacturing-control) endpoints and requires separate safety packages. Demonstrating superiority over standard-of-care in adequately powered Phase II/III trials can exceed USD 20 million; without compelling overall-survival benefit, reimbursement may be denied [84], [85].

6.2 Future Directions

Precision Nanomedicine

Real-time PET/MR imaging and liquid-biopsy-derived exosomal signatures will enable patient-specific adjustment of ligand density, stimulus threshold or drug-to-carrier ratio.

Imaging techniques (including perfusion MRI) are used in clinical trials to predict nanomedicine accumulation and efficacy, enabling prospective patient stratification [86].

Next-Generation Materials

Enzymatically cleavable peptides and DNA origami scaffolds degrade to non-toxic nucleotides or amino acids, eliminating long-term accumulation concerns. In situ swelling or charge-reversal systems (e.g., from 20 mV to +10 mV at pH 6.5) are being engineered to enhance diffusion across 100-200 μm tumor rims.[87]

Multimodal Theranostics

Hybrid nano-probes labelled with ^{64}Cu for PET, Gd for T_1-weighted MRI and indocyanine green for NIR fluorescence allow simultaneous whole-body biodistribution and intra-operative margin assessment [88]. Closed-loop feedback algorithms are being developed to modulate PTT laser power or PDT drug-light intervals in real time based on intra-tumoral oxygenation [89].

Cross-Disciplinary Integration

Regulatory science consortia (FDA-NCI Nanotechnology Characterization Laboratory, EMA-IMI) now provide standardized protocols for physicochemical characterization, immunotoxicity and large-animal pharmacokinetics [90].

VII. CONCLUSION

TME-responsive nanoplatforms have emerged as a disruptive strategy to overcome the pharmacological and biological barriers that limit conventional HNC therapy. By harnessing hypoxia, acidic pH, ECM stiffness and immunosuppression as endogenous triggers, these systems simultaneously enhance tumor accumulation, minimize systemic exposure and enable real-time imaging feedback. Although long-term biodistribution, manufacturing reproducibility and patient heterogeneity remain critical hurdles, converging advances in precision imaging, adaptive materials design and regulatory science are accelerating clinical translation. Continued interdisciplinary validation will be essential to transform these pre-clinical successes into personalised nanotherapeutics for head-and-neck cancer.

DATA AVAILABILITY STATEMENT

The authors confirm that all data generated or analyzed during this review are included in this article.

DECLARATION OF COMPETING INTEREST

The authors state that they have no competing financial interests or personal relationships that may have influenced the findings in this paper.

FUNDING

This work was supported by China National Natural Science Foundation (11602159), Natural Science Foundation of Shanxi province (202103021224108), Research Project Supported by Shanxi Scholarship Council of China (2023-072).

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International Journal of Advanced Engineering Research and Science (IJAERS)
Peer-Reviewed Journal
ISSN: 2349-6495(P) | 2456-1908(O)
Vol-12, Issue-10; Oct, 2025
Journal Home Page Available: https://ijaers.com/
Article DOI: https://dx.doi.org/10.22161/ijaers.1210.2

Time Series Water Wave Model Based on Energy Conservation

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Received: 03 Sep 2025,

Received in revised form: 02 Oct 2025,

Accepted: 06 Oct 2025,

Available online: 13 Oct 2025

***Keywords*— energy conservation, solitary wave profile, shoaling-breaking**

***Abstract*— The time series water wave model comprises two equations: the water surface elevation equation and the water particle velocity equation. The elevation equation, derived from the continuity equation, captures changes in potential energy but lacks an energy source. The velocity equation describes changes in kinetic energy but does not include potential energy contributions. In this research, the energy deficiency in the elevation equation is addressed by combining it with the conservation of kinetic energy, while the velocity equation incorporates a driving force derived from the continuity equation. Both equations use a weighted Taylor series expansion to produce realistic wavelengths consistent with natural waves. The model is executed using a periodic solitary wave input, defined as a profile in which the trough and crest lie above the still water level. This input satisfies the initial conditions at the entry point, where the water surface elevation and its time derivative are zero. Shoaling and breaking analysis with the developed model yielded breaking parameters that agree with previous research.*

I. INTRODUCTION

Time series models are widely applied in water wave analysis. The Boussinesq equation (1871) has been the most extensively developed and utilized. Subsequent refinements have been made by numerous scholars, including Peregrine (1967), Hamm and Madsen (1993), Nwogu (1993), Dingemans (1997), Johnson (1997), Madsen and Schaffer (1998), and Kirby (2003).

The Airy long-wave equation, originally introduced for tidal wave modeling (Dean, 1991), shares the same fundamental structure as the Boussinesq formulation and can therefore be regarded as a special case within the Boussinesq framework.

A well-known limitation of the Boussinesq equation is its applicability to only small wave amplitudes. To address this, Hutahaean (2005a) combined the continuity and energy conservation equations to produce a model capable of representing larger wave amplitudes for a given wave period. Later, Hutahaean (2025a) refined the convective acceleration term in the velocity equation, though without modifying the surface elevation equation, thereby advancing the time series model for use with larger wave amplitudes.

Despite these advances, time series models still face challenges in representing wave transformation from deep to shallow water. While shoaling effects can be reasonably simulated, wave breaking remains difficult to capture accurately.

Hutahaean (2024a, 2024b) developed a time series model based on the water surface elevation equation, formulated as a superposition of the continuity and kinetic energy conservation equations, without further refinement of the velocity equation. Both equations were derived using a weighted Taylor series, producing short wavelengths that closely approximate those observed in nature. However, the model remained limited in its ability to simulate wave breaking.

Another challenge in time series modeling concerns wave input. With sinusoidal input, the initial condition at the input point (zero) is not satisfied. According to the

Kinematic Free Surface Boundary Condition, the water particle velocity at this point should be zero, yet it is instead at its maximum. This inconsistency introduces errors, particularly in short-wave modeling, where vertical water particle velocity is a key variable.

The present research addresses these limitations by incorporating energy conservation into both the water surface elevation and velocity equations. The convective acceleration term in the velocity equation was further refined by interpreting it as a hydrodynamic force (Hutahaean, 2025a). To achieve wavelengths consistent with those found in nature, the formulation again employs a weighted Taylor series. The model proposed in this research employs a periodic solitary wave profile to ensure that both the water surface elevation and its differential are zero at the initial calculation point.

II. DEPTH AVERAGE VELOCITY, INTEGRATION COEFFICIENT AND TRANSFORMATION COEFFICIENT

In formulating the water surface elevation and horizontal water particle velocity equations, integration with respect to water depth is performed using the concept of depth-averaged velocity. Accordingly, both equations are expressed in terms of depth-averaged velocity. Since the formulation also involves surface particle velocity, this quantity must be transformed into its depth-averaged equivalent. Depth-averaged velocity is defined as the velocity at an elevation $z_0$below the still water level (Fig 1).

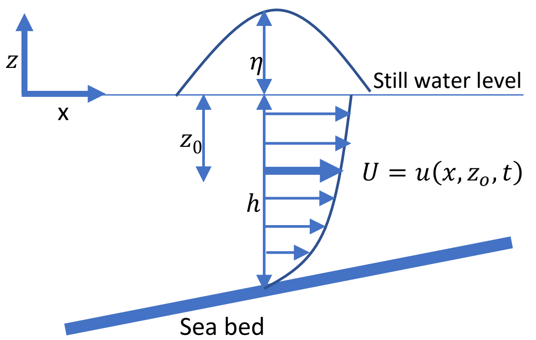

Fig (1). Depth average velocity definition.

From the velocity potential equation,

$$\phi(x,z,t) = 2\,G \cos kx \cosh k(h+z) \sin \sigma t \quad \dots (1)$$

G is the wave constant, $k = \frac{2\pi}{L}$ is the wave number and L is the wavelength, $\sigma = \frac{2\pi}{T}$ is the angular frequency, T is the wave period.

Horizontal water particle velocity is,

$$u(x,z,t) = -\frac{\partial \phi}{\partial x}$$
$$= 2\,Gk \sin kx \cosh k(+z) \sin \sigma t \quad \dots (2)$$

According to the definition, the depth-averaged horizontal water particle velocity is,

$$U = u(x, z_0, t) = 2\,Gk \sin kx \cosh k(h + z_0) \sin \sigma t \quad \dots (3)$$

The vertical water particle velocity is expressed as,

$$w(x,z,t) = -\frac{\partial \phi}{\partial z}$$
$$= -2\,Gk \cos kx \sinh k(h+z) \sin \sigma t \quad \dots (4)$$

Accordingly, the depth-averaged vertical water particle velocity is,

$$W = w(x, z_0, t)$$
$$= -2\,Gk \cos kx \sinh k(+z) \sin \sigma t \quad \dots (5)$$

2.1. Integration coefficient and transformation coefficient.

a. Integration coefficient of water particle velocity β_u , β_{uu}, β_{uuu} and β_{ww}.

a.1. Integration coefficient β_u

The integration of the horizontal water particle velocity, as defined by Dean (1991) is

$$\int_{-h}^{\eta} u\, dz = \beta_u U D \quad \dots (6)$$

$U = u(x, z_0, t)$ is the depth average velocity, total water depth $D = h + \eta$, h is the water depth towards still water level Fig (1), and β_u is the integration- coefficient. Thus, the integration coefficient equation of β_u is,

$$\beta_u = \frac{\int_{-h}^{\eta} u\, dz}{UD}$$

From (2) and (3),

$$\beta_u = \frac{\int_{-h}^{\eta} 2\,Gk \sin kx \cosh k(h+z) \sin \sigma t\ dz}{D\ 2\,Gk \sin kx \cosh k(h+z_0) \sin \sigma t}$$

Common terms in the numerator and denominator cancel, and upon evaluating the integral, one obtains,

$$\beta_u = \frac{\sinh k(h+\eta)}{kD\ \cosh k(h+z_0)} \quad \dots (7)$$

From the wave number conservation relation (Hutahaean, 2023),

$$k(h+\eta) = kD = \theta\pi \quad \dots (8)$$

Where θ is the deep water coefficient with $\tanh \theta\pi \approx 1$, therefore (7) is

$$\beta_u = \frac{\sinh \theta\pi}{\theta\pi\ \cosh kh(1 + \frac{z_0}{h})}$$

For $\varepsilon = \left|\frac{z_0}{h}\right|$

$$\beta_u = \frac{\sinh\theta\pi}{\theta\pi\ \cosh kh(1-\varepsilon)}$$

With the small amplitude approach, $kh = \theta\pi$

$$\beta_u = \frac{\sinh\theta\pi}{\theta\pi\ \cosh\theta\pi(1-\varepsilon)} \qquad \text{... (9)}$$

a.2. Integration coefficient β_{uu}

Is defined as,

$$\beta_{uu} = \frac{\int_{-h}^{\eta} uu\, dz}{UUD} \qquad \text{... (10)}$$

Substituting (2) and (3), and following the same procedure as in the derivation of β_u yields,

$$\beta_{uu} = \frac{\left(\frac{1}{2}\sinh 2\theta\pi + \theta\pi\right)}{2\theta\pi\ cosh^2\theta\pi(1-\varepsilon)} \qquad \text{... (11)}$$

a.3. Integration coefficient β_{uuu}

Is defined as,

$$\beta_{uuu} = \frac{\int_{-h}^{\eta} uuu\, dz}{UUUD} \qquad \text{... (12)}$$

Substituting (2) and (3), and following the same steps as in the derivation of β_u results,

$$\beta_{uuu} = \frac{\frac{1}{3}\sinh 3\theta\pi + 3\sinh\theta\pi}{8\theta\pi cosh^3\theta\pi(1-\varepsilon)} \qquad \text{.. (13)}$$

a.4. Integration coefficient β_{ww}

Is defined as,

$$\beta_{ww} = \frac{\int_{-h}^{\eta} ww\, dz}{WWD} \qquad \text{... (14)}$$

By substituting (4) and (5), and following the same procedure as in the derivation of β_u as follows

$$\beta_{ww} = \frac{\left(\frac{1}{2}\sinh 2\theta\pi - \theta\pi\right)}{2\theta\pi\ cosh^2\theta\pi(1-\varepsilon)} \qquad \text{... (15)}$$

b. Transformation coefficient $\alpha_{u\eta}$ and $\alpha_{w\eta}$

The relationship between the horizontal surface water particle velocity and the horizontal depth-averaged water particle velocity is expressed as,

$$u_\eta = \alpha_{u\eta} U$$

u_η is the surface horizontal water particle velocity, $\alpha_{u\eta}$ is the transformation-coefficient,

$$\alpha_{u\eta} = \frac{\cosh\theta\pi}{\cosh\theta\pi(1-\varepsilon)} \qquad \text{... (16)}$$

Similarly, the vertical transformation coefficient is obtained as,

$$\alpha_{w\eta} = \frac{\sinh\theta\pi}{\sinh\theta\pi(1-\varepsilon)} \qquad \text{... (17)}$$

In this research, a value of $\theta = 1.00$, where $\tanh\theta\pi = 0.996272$ is close to 1.0. The corresponding values of the integration coefficients for θ is presented in Table (1).

Table (1). The Values of Integration Coefficient.

ε	β_u	β_{uu}	β_{uuu}	β_{ww}
0.37	0.99688	1.60363	1.66625	1.65154
0.371	0.99990	1.61335	1.68143	1.66236
0.372	1.00293	1.62314	1.69675	1.67325
0.373	1.00596	1.63298	1.71220	1.68421
0.374	1.00901	1.64287	1.72779	1.69525
0.375	1.01206	1.65283	1.74352	1.70637
0.376	1.01512	1.66284	1.75939	1.71756
0.377	1.01819	1.67291	1.77539	1.72882
0.378	1.02127	1.68304	1.79154	1.74017
0.379	1.02435	1.69323	1.80783	1.75159

The values of the integration coefficients employed in this research correspond to those for which β_u is closest to, or equal to, 1.0. As shown in Table 1, $\beta_u \approx 1$ occurs at $\varepsilon = 0.371$. Therefore, the integration coefficients β_u, β_{uu}, β_{uuu} and β_{ww} is the value at $\varepsilon = 0.371$. Similarly, the transformation coefficients presented in Table 2 are also evaluated at $\varepsilon = 0.371$.

Table (2). The values of transformation coefficient

ε	$\alpha_{u\eta}$	$\alpha_{w\eta}$
0.37	3.14352	3.25372
0.371	3.15303	3.26436
0.372	3.16258	3.27503
0.373	3.17215	3.28575
0.374	3.18175	3.29650
0.375	3.19137	3.30729
0.376	3.20103	3.31811
0.377	3.21071	3.32898
0.378	3.22041	3.33988
0.379	3.23014	3.35082

III. INTEGRAL SOLUTION USING THE VELOCITY POTENTIAL EQUATION

In the formulation of the velocity equations in Section V, an integration appears that can be solved by applying the velocity potential. This section presents the procedure for evaluating the integral. The integral to be solved is $\frac{\partial}{\partial x}\int_z^\eta\left(\frac{\partial}{\partial t}\int_z^\eta\frac{\partial u}{\partial x}\,dz\right)dz$.

From (2), the following is obtained

$$\frac{\partial u}{\partial x}=2Gk^2\cos kx\cosh k(h+z)\sin\sigma t$$

$$\int_z^\eta\frac{\partial u}{\partial x}\,dz=2Gk\cos kx$$
$$(\sinh k(h+\eta)-\sinh k(h+z))\sin\sigma t$$

Considering (4), hence

$$\int_z^\eta\frac{\partial u}{\partial x}\,dz=-w_\eta+w$$

therefore,

$$\frac{\partial}{\partial t}\int_z^\eta\frac{\partial u}{\partial x}\,dz=-\frac{\partial w_\eta}{\partial t}+\frac{\partial w}{\partial t}$$

Integrating with respect to

$$\int_z^\eta\left(\frac{\partial}{\partial t}\int_z^\eta\frac{\partial u}{\partial x}\,dz\right)dz=-\frac{\partial w_\eta}{\partial t}(\eta-z)+\int_z^\eta\frac{\partial w}{\partial t}dz$$

$$\frac{\partial}{\partial x}\int_z^\eta\left(\frac{\partial}{\partial t}\int_z^\eta\frac{\partial u}{\partial x}\,dz\right)dz=-\frac{\partial w_\eta}{\partial t}\frac{\partial\eta}{\partial x}+\frac{\partial}{\partial x}\int_z^\eta\frac{\partial w}{\partial t}dz$$

Using (4),

$$\int_z^\eta\frac{\partial w}{\partial t}\,dz=-2G\sigma\cos kx$$
$$(\cosh k(h+\eta)-\cosh k(h+z))\cos\sigma t$$

Therefore

$$\frac{\partial}{\partial x}\int_z^\eta\frac{\partial w}{\partial t}\,dz=2Gk\sigma\sin kx$$
$$(\cosh k(h+\eta)-\cosh k(h+z))\cos\sigma t$$

From (2), obtains

$$\frac{\partial}{\partial x}\int_z^\eta\frac{\partial w}{\partial t}\,dz=\left(\frac{\partial u_\eta}{\partial t}-\frac{\partial u}{\partial t}\right)$$

The final result is,

$$\frac{\partial}{\partial x}\int_z^\eta\left(\frac{\partial}{\partial t}\int_z^\eta\frac{\partial u}{\partial x}\,dz\right)dz=$$
$$-\frac{\partial w_\eta}{\partial t}\frac{\partial\eta}{\partial x}+\left(\frac{\partial u_\eta}{\partial t}-\frac{\partial u}{\partial t}\right)\quad\ldots(18)$$

IV. WATER SURFACE ELEVATION EQUATION

The water surface elevation equation is formulated using the continuity equation and the principle of energy conservation.

a. Continuity Equation

The continuity equation, derived from the principle of mass conservation in the (x,z) plane is expressed as,

$$\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}=0\quad\ldots(19)$$

Integrating this equation along the vertical axis$-z$ from seabed $z=-h$, to water surface $z=\eta$ and substituting the weighted Kinematic Free Surface Boundary Condition, yields,

$$\int_{-h}^\eta\frac{\partial u}{\partial x}\,dz+w_\eta-w_{-h}=0$$

Weighted Kinematic Free Surface Boundary Condition is,

$$w_\eta=\gamma_{t,2}\frac{\partial\eta}{\partial t}+\gamma_{x,2}u_\eta\frac{\partial\eta}{\partial x}\quad\ldots(20)$$

where $\gamma_{t,2}$ and $\gamma_{x,2}$ is the weighting coefficients for funcion $f=f(x,t)$. In this research, the values $\gamma_{t,2}=1.9973$ and $\gamma_{x,2}=0.9973$ is used. The computational method for these coefficients can be found in Hutahaean (2025b).

$$\int_{-h}^\eta\frac{\partial u}{\partial x}\,dz+\gamma_{t,2}\frac{\partial\eta}{\partial t}+\gamma_{x,2}u_\eta\frac{\partial\eta}{\partial x}-w_{-h}=0$$

This equation is subsequently expressed as the water surface elevation equation.,

$$\gamma_{t,2}\frac{\partial\eta}{\partial t}=-\int_{-h}^\eta\frac{\partial u}{\partial x}\,dz-\gamma_{x,2}u_\eta\frac{\partial\eta}{\partial x}+w_{-h}$$

The integration of the first term on the right-hand side is evaluated using Leibniz's rule of integration (Protter, Murray, Morrey, & Charles, 1985),

$$\int_\alpha^\beta\frac{\partial f}{\partial x}dz=\frac{\partial}{\partial x}\int_\alpha^\beta u\,dz-f_\beta\frac{\partial\beta}{\partial x}+f_\alpha\frac{\partial\alpha}{\partial x}\quad\ldots(21)$$

Thus,

$$\int_{-h}^\eta\frac{\partial u}{\partial x}dz=\frac{\partial}{\partial x}\int_{-h}^\eta u\,dz-u_\eta\frac{\partial\eta}{\partial x}-u_{-h}\frac{\partial h}{\partial x}$$

Accordingly,

$$\gamma_{t,2}\frac{\partial\eta}{\partial t}=-\frac{\partial}{\partial x}\int_{-h}^\eta u\,dz+u_\eta\frac{\partial\eta}{\partial x}$$
$$+u_{-h}\frac{\partial h}{\partial x}-\gamma_{x,2}u_\eta\frac{\partial\eta}{\partial x}+w_{-h}$$

Applying the seabed kinematic boundary condition, $w_{-h}=-u_{-h}\frac{\partial h}{\partial x}$ the third and fifth terms on the right-hand side cancel out. The first term is then expressed using the concept of depth-averaged velocity (6), while the surface horizontal velocity u_η is transformed into the depth-averaged velocity U.

$$\gamma_{t,2}\frac{\partial\eta}{\partial t}=-\frac{\partial\beta_u UD}{\partial x}+\left(1-\gamma_{x,2}\right)\alpha_{u\eta}U\frac{\partial\eta}{\partial x}\quad ...(22)$$

This equation represents the water surface elevation equation derived from the continuity principle. In this formulation, the left-hand side expresses the change in potential energy, yet no source of energy appears on the right-hand side. The missing source term should correspond to kinetic energy. Therefore, this equation must be superimposed with the kinetic energy conservation equation.

b. Energy Conservation Equation

The kinetic energy conservation equation as formulated by Hutahaean (2024b) is expressed as follows,

$$\frac{\partial E_{kx}}{\partial t}+\frac{\partial E_{kz}}{\partial t}=-\frac{\partial uE_{kx}}{\partial x}-\frac{\partial wE_{kz}}{\partial z}\quad ..(23)$$

$E_{kx}=\frac{uu}{2g}$, represents the kinetic energy of the horizontal velocity component, and $E_{kz}=\frac{ww}{2g}$, represents the kinetic energy of the vertical velocity component. Equation (23) is then multiplied by dz and integrated with respect to the vertical axis-z,

$$\int_{-h}^{\eta}\frac{\partial E_{kx}}{\partial t}dz+\int_{-h}^{\eta}\frac{\partial E_{kz}}{\partial t}dz=-\int_{-h}^{\eta}\frac{\partial uE_{kx}}{\partial x}dz-\frac{w_\eta w_\eta w_\eta}{2g}\quad ..(24)$$

Where $\frac{w_{-h}w_{-h}w_{-h}}{2g}$ is neglected. The integration is solved using the Leibniz integration rule,

$$\int_{-h}^{\eta}\frac{\partial E_{kx}}{\partial t}dz=\frac{1}{2g}\frac{\partial}{\partial t}\int_{-h}^{\eta}uu\,dz-\frac{u_\eta u_\eta}{2g}\frac{\partial\eta}{\partial t}$$

The right-hand side is evaluated using the concept of depth-averaged velocity,

$$\int_{-h}^{\eta}\frac{\partial E_{kx}}{\partial t}dz=\frac{1}{2g}\frac{\partial\beta_{uu}UUD}{\partial t}-\frac{u_\eta u_\eta}{2g}\frac{\partial\eta}{\partial t}$$

Considering that $D=h+\eta$ and $u_\eta=\alpha_{u\eta}U$,

$$\int_{-h}^{\eta}\frac{\partial E_{kx}}{\partial t}dz=\frac{\beta_{uu}D}{2g}\frac{\partial UU}{\partial t}+\left(\beta_{uu}-\alpha_{u\eta}\alpha_{u\eta}\right)\frac{UU}{2g}\frac{\partial\eta}{\partial t}$$

In a similar way, the following is obtained:

$$\int_{-h}^{\eta}\frac{\partial E_{kz}}{\partial t}dz=\frac{\beta_{ww}D}{2g}\frac{\partial WW}{\partial t}+\left(\beta_{ww}-\alpha_{w\eta}\alpha_{w\eta}\right)\frac{WW}{2g}\frac{\partial\eta}{\partial t}$$

By substituting the results of these integrations into Equation (23), we obtain the following expression:

$$\lambda\frac{\partial\eta}{\partial t}=-\frac{1}{2g}\frac{\partial UU}{\partial t}-\frac{\beta_{ww}}{2g\beta_{uu}}\frac{\partial WW}{\partial t}-\frac{1}{2g\beta_{uu}D}\int_{-h}^{\eta}\frac{\partial uE_{kx}}{\partial x}dz-\frac{1}{2g\beta_{uu}D}w_\eta w_\eta w_\eta\quad ...(25)$$

Where,

$$\lambda=\frac{\left(\left(\beta_{uu}-\alpha_{u\eta}\alpha_{u\eta}\right)UU+\left(\beta_{ww}-\alpha_{w\eta}\alpha_{w\eta}\right)WW\right)}{2g\beta_u D}$$

The term g on both the left-hand side and the right-hand side cannot be eliminated, as doing so would result in inconsistent dimensional units for $\frac{\partial\eta}{\partial t}$ and cannot be undergo superposition with $\frac{\partial\eta}{\partial t}$ within the continuity equation. The integration of the third term on the right-hand side can be solved using Leibniz integration and the concept of depth-averaged velocity,

$$\frac{1}{2g}\int_{-h}^{\eta}\frac{\partial uuu}{\partial x}dz=\frac{\beta_{uuu}}{2g}\frac{\partial UUUD}{\partial x}-\frac{u_\eta u_\eta u_\eta}{2g}\frac{\partial\eta}{\partial x}-u_{-h}u_{-h}u_{-h}\frac{\partial h}{\partial x}$$

By neglecting the term $u_{-h}u_{-h}u_{-h}\frac{\partial h}{\partial x}$ and transforming $\frac{u_\eta u_\eta u_\eta}{2g}=\frac{\alpha_{u\eta}\alpha_{u\eta}\alpha_{u\eta}UUU}{2g}$.

$$\frac{1}{2g}\int_{-h}^{\eta}\frac{\partial uuu}{\partial x}dz=\frac{\beta_{uuu}}{2g}\frac{\partial UUUD}{\partial x}-\frac{\alpha_{u\eta}\alpha_{u\eta}\alpha_{u\eta}}{2g}UUU\frac{\partial\eta}{\partial x}$$

Subsequently, Equation (22) is superposed with Equation (25), yielding:

$$\gamma_{t,2}\frac{\partial\eta}{\partial t}=-\frac{\partial\beta_u UD}{\partial x}+\left(1-\gamma_{x,2}\right)\alpha_{u\eta}U\frac{\partial\eta}{\partial x}$$

$$\lambda\frac{\partial\eta}{\partial t}=-\frac{1}{2g}\frac{\partial UU}{\partial t}-\frac{\beta_{ww}}{2g\beta_{uu}}\frac{\partial WW}{\partial t}-\frac{1}{2g\beta_{uu}D}\int_{-h}^{\eta}\frac{\partial uE_{kx}}{\partial x}dz-\frac{1}{2g\beta_{uu}D}w_\eta w_\eta w_\eta$$

$$\left(\gamma_{t,2}+\lambda\right)\frac{\partial\eta}{\partial t}=-\frac{\partial\beta_u UD}{\partial x}+\left(1-\gamma_{x,2}\right)\alpha_{u\eta}U\frac{\partial\eta}{\partial x}-\frac{1}{2g}\frac{\partial UU}{\partial t}-\frac{\beta_{ww}}{2g\beta_{uu}}\frac{\partial WW}{\partial t}-\frac{1}{2g\beta_{uu}D}\int_{-h}^{\eta}\frac{\partial uE_{kx}}{\partial x}dz-\frac{1}{2g\beta_{uu}D}w_\eta w_\eta w_\eta\quad ...(26)$$

Equation (26) represents the water surface elevation equation, which is used to calculate $\eta(x,t)$.

V. HORIZONTAL WATER PARTICLE VELOCITY EQUATION

The horizontal water particle velocity equation is derived using the Euler momentum conservation equations.

5.1. Euler Momentum Conservation Equations.

The Euler momentum conservation equations for flow in the (x, z) plane consist of two parts: the particle velocity equation in the horizontal direction and the particle velocity equation in the vertical direction. By employing the concept of weighted total acceleration, these equations are expressed as follows:

Horizontal particle velocity equation,

$$\gamma_{t,3}\frac{\partial u}{\partial t}+\gamma_{x,3}\,u\frac{\partial u}{\partial x}+\gamma_{z,3}\,w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x} \qquad .(27)$$

Vertical particle velocity equation,

$$\gamma_{t,3}\frac{\partial w}{\partial t}+\gamma_{x,3}u\frac{\partial w}{\partial x}+\gamma_{z,3}\,w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}-g \qquad ..(28)$$

ρ is the water density, p s the pressure acting on the fluid particle, and g is the gravitational acceleration.

Equations (27) and (28) are formulated under the condition that the horizontal particle velocity u varies with respect to both the horizontal axis -x and the vertical axis -z, while the vertical particle velocity w similarly varies with respect to both axes. In this research, however, the Euler momentum conservation equations are developed under the assumption that the horizontal velocity u varies only along the horizontal axis -x and the vertical velocity w varies only along the vertical axis -z. This assumption ensures consistency with the formulation of the continuity equation as follows.

$$\gamma_{t,3}\frac{\partial u}{\partial t}+\frac{\gamma_{x,3}}{2}\frac{\partial uu}{\partial x}=-\frac{1}{\rho}\frac{\partial p}{\partial x} \qquad ....(29)$$

$$\gamma_{t,3}\frac{\partial w}{\partial t}+\frac{\gamma_{z,3}}{2}\frac{\partial ww}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}-g \qquad ...(30)$$

$\gamma_{t,3}$, $\gamma_{x,3}$ and $\gamma_{z,3}$ are the weighting coefficients in the weighted Taylor series. This research employed $\gamma_{t,3}=3.04933$ and $\gamma_{x,3}=\gamma_{z,3}=2.04933$, which calculation method of the weighting coefficients referred to Hutahaean (2025b).

The horizontal water particle velocity equation is formulated using Equations (29) and (30), with the pressure equation p derived first. To ensure a strong interaction between the velocity equation and the continuity equation, the formulation of pressure p is based on the continuity equation. Integrating the continuity equation along the vertical axis-z, the following is obtained

$$\int_z^\eta \frac{\partial u}{\partial x}dz+w_\eta-w=0$$

Differentiating this equation with respect to time-t yields an expression for $\frac{\partial w}{\partial t}$,

$$\frac{\partial w}{\partial t}=\frac{\partial}{\partial t}\int_z^\eta \frac{\partial u}{\partial x}dz+\frac{\partial w_\eta}{\partial t}$$

Substituting to (30),

$$\gamma_{t,3}\left(\frac{\partial}{\partial t}\int_z^\eta \frac{\partial u}{\partial x}dz+\frac{\partial w_\eta}{\partial t}\right)+\frac{\gamma_{z,3}}{2}\frac{\partial ww}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}-g$$

This expression is then rearranged into an equation for pressure p , which is integrated over the water depth from $z=z$ to $z=\eta$ applying the dynamic surface boundary condition $p_\eta=0$. This yields the following pressure equation p.

$$\frac{p}{\rho}=\gamma_{t,3}\int_z^\eta\left(\frac{\partial}{\partial t}\int_z^\eta \frac{\partial u}{\partial x}dz\right)dz+\frac{\gamma_{z,3}}{2}\left(w_\eta w_\eta-ww\right)+\left(g+\gamma_{t,3}\frac{\partial w_\eta}{\partial t}\right)(\eta-z)$$

Differentiating with respect to the horizontal axis-x, while neglecting the cross-differential term, $\frac{\partial}{\partial x}\left(\frac{\partial w_\eta}{\partial t}\right)$,

$$\frac{1}{\rho}\frac{\partial p}{\partial x}=\gamma_{t,3}\frac{\partial}{\partial x}\int_z^\eta\left(\frac{\partial}{\partial t}\int_z^\eta \frac{\partial u}{\partial x}dz\right)dz+\frac{\gamma_{z,3}}{2}\frac{\partial}{\partial x}\left(w_\eta w_\eta-ww\right)+\left(g+\gamma_{t,3}\frac{\partial w_\eta}{\partial t}\right)\frac{\partial\eta}{\partial x} \qquad ..(31)$$

5.2. Formulation Using the Direct Method

Equation (31) is substituted into Equation (29) and evaluated at $z=\eta$ known as the direct method.

$$\gamma_{t,3}\frac{\partial u_\eta}{\partial t}+\frac{\gamma_{x,3}}{2}\frac{\partial u_\eta u_\eta}{\partial x}=-\left(g+\gamma_{t,3}\frac{\partial w_\eta}{\partial t}\right)\frac{\partial\eta}{\partial x}$$

The second term on the left-hand side is assigned a negative sign, based on the assumption that it represents the hydrodynamic force acting in the direction of energy transfer from higher to lower energy states (Hutahaean, 2025a). The equation can therefore be rearranged as:

$$\gamma_{t,3}\frac{\partial u_\eta}{\partial t}=\frac{\gamma_{x,3}}{2}\frac{\partial u_\eta u_\eta}{\partial x}-\left(g+\gamma_{t,3}\frac{\partial w_\eta}{\partial t}\right)\frac{\partial\eta}{\partial x}$$

Next, the variables on the left-hand side and the first term on the right-hand side are transformed into depth-averaged velocity form,

$$\gamma_{t,3}\alpha_{u\eta}\frac{\partial U}{\partial t}=\frac{\gamma_{x,3}\alpha_{u\eta}\alpha_{u\eta}}{2}\frac{\partial UU}{\partial x}-\left(g+\gamma_{t,3}\frac{\partial w_\eta}{\partial t}\right)\frac{\partial\eta}{\partial x} \qquad ...(32)$$

The term $\frac{\partial w_\eta}{\partial t}$ on the right-hand side is expressed using the continuity equation. Integrating the continuity equation

(19) along the vertical axis-z, from $z = -h$ to $z = \eta$, applying the Leibniz integration rule, the depth-averaged velocity concept, and the seabed kinematic boundary condition, yields,

$$w_\eta = -\frac{\partial \beta_u U D}{\partial x} + u_\eta \frac{\partial \eta}{\partial x}$$

By neglecting second-order differentials and cross-differentials, the following relation is obtained:

$$\frac{\partial w_\eta}{\partial t} = -\beta_u \frac{\partial U}{\partial x}\frac{\partial \eta}{\partial t} + \left(\alpha_{u\eta}\frac{\partial \eta}{\partial x} - \beta_u \frac{\partial D}{\partial x}\right)\frac{\partial U}{\partial t} \quad \ldots (33)$$

Substituting to (32),

$$\gamma_{t,3}\left(\alpha_{u\eta} + \left(\alpha_{u\eta}\frac{\partial \eta}{\partial x} - \beta_u \frac{\partial D}{\partial x}\right)\frac{\partial \eta}{\partial x}\right)\frac{\partial U}{\partial t} = \frac{\gamma_{x,3}\alpha_{u\eta}\alpha_{u\eta}}{2}\frac{\partial UU}{\partial x} - \left(g - \gamma_{t,3}\beta_u \frac{\partial U}{\partial x}\frac{\partial \eta}{\partial t}\right)\frac{\partial \eta}{\partial x} \quad \ldots (34)$$

In the second term on the right-hand side, the parameter $\frac{\partial \eta}{\partial t}$ appears, which represents the source of energy contributing to changes in kinetic energy on the left-hand side.

This equation does not contain the variable water depth. As a result, the shoaling-breaking modeling based on this formulation produces large breaking wave heights, occurring only in very shallow waters.

For this reason, a subsequent model was developed using the integration method, which incorporates the water depth variable into the formulation.

5.3. Formulation with the Integration Method

In this section, the formulation of the velocity equation is carried out through integration, hence it is referred to as the integration method. The integration of the first term on the right-hand side of Equation (31) is performed using the velocity potential equation (1), yielding Equation (18). Substituting Equation (18) into (31) gives:

$$\frac{1}{\rho}\frac{\partial p}{\partial x} = \gamma_{t,3}\left(\frac{\partial u_\eta}{\partial t} - \frac{\partial u}{\partial t}\right) + \frac{\gamma_{z,3}}{2}\frac{\partial w_\eta w_\eta}{\partial x} - \frac{\gamma_{z,3}}{2}\frac{\partial ww}{\partial x} + g\frac{\partial \eta}{\partial x}$$

Substituting (29),

$$\gamma_{t,3}\frac{\partial u_\eta}{\partial t} + \frac{\gamma_{x,3}}{2}\frac{\partial uu}{\partial x} = -\frac{\gamma_{z,3}}{2}\frac{\partial w_\eta w_\eta}{\partial x} + \frac{\gamma_{z,3}}{2}\frac{\partial ww}{\partial x} - g\frac{\partial \eta}{\partial x}$$

The second term on the left-hand side, as well as the first and second terms on the right-hand side, represent hydrodynamic forces directed positively from higher to lower energy. Therefore, following Hutahaean (2025b),

$$\gamma_{t,3}\frac{\partial u_\eta}{\partial t} - \frac{\gamma_{x,3}}{2}\frac{\partial uu}{\partial x} = \frac{\gamma_{z,3}}{2}\frac{\partial w_\eta w_\eta}{\partial x} - \frac{\gamma_{z,3}}{2}\frac{\partial ww}{\partial x} - g\frac{\partial \eta}{\partial x}$$

Integrating with respect to the vertical axis-z,

$$\gamma_{t,3}D\frac{\partial u_\eta}{\partial t} - \frac{\gamma_{x,3}}{2}\int_{-h}^{\eta}\frac{\partial uu}{\partial x}dz = \frac{\gamma_{z,3}D}{2}\frac{\partial w_\eta w_\eta}{\partial x} - \frac{\gamma_{z,3}}{2}\int_{-h}^{\eta}\frac{\partial ww}{\partial x}dz - gD\frac{\partial \eta}{\partial x}$$

Dividing through by D, and transforming the first term on the left-hand side into the depth-averaged velocity, gives:

$$\gamma_{t,3}\alpha_{u\eta}\frac{\partial U}{\partial t} = \frac{\gamma_{x,3}}{2D}\int_{-h}^{\eta}\frac{\partial uu}{\partial x}dz + \frac{\gamma_{z,3}}{2}\frac{\partial w_\eta w_\eta}{\partial x} - \frac{\gamma_{z,3}}{2D}\int_{-h}^{\eta}\frac{\partial ww}{\partial x}dz - g\frac{\partial \eta}{\partial x} \quad \ldots (35)$$

In this equation, the parameter $\frac{\partial \eta}{\partial t}$ does not appear explicitly; however, it is implicitly contained in the term w_η (second term on the right-hand side) and in w (third term on the right-hand side).

Equation (35) thus serves as the governing relation for computing the depth-averaged horizontal velocity. By neglecting seabed velocity, the integrals are expressed as,

$$\int_{-h}^{\eta}\frac{\partial uu}{\partial x}dz = \beta_{uu}\frac{\partial UUD}{\partial x} - u_\eta u_\eta \frac{\partial \eta}{\partial x}$$

$$\int_{-h}^{\eta}\frac{\partial ww}{\partial x}dz = \beta_{ww}\frac{\partial WWD}{\partial x} - w_\eta w_\eta \frac{\partial \eta}{\partial x}$$

The shoaling-breaking modeling based on the velocity equation (35) predicts that waves undergo breaking more readily, with breaking occurring at water depths that are still relatively large.

5.4. Final Form of the Horizontal Velocity Equation

The final form of the horizontal water particle velocity equation is obtained by combining equations (34) and (35), with the composition defined as α_1x (34) + α_2 x ((35), where $\alpha_1 + \alpha_2 = 1.0$.

$$\alpha_1\gamma_{t,3}\left(\alpha_{u\eta} + \left(\alpha_{u\eta}\frac{\partial \eta}{\partial x} - \beta_u\frac{\partial D}{\partial x}\right)\frac{\partial \eta}{\partial x}\right)\frac{\partial U}{\partial t} = \alpha_1\left(\frac{\gamma_{x,3}\alpha_{u\eta}\alpha_{u\eta}}{2}\frac{\partial UU}{\partial x} - \left(g - \gamma_{t,3}\beta_u\frac{\partial U}{\partial x}\frac{\partial \eta}{\partial t}\right)\frac{\partial \eta}{\partial x}\right)$$

$$\alpha_2\gamma_{t,3}\alpha_{u\eta}\frac{\partial U}{\partial t} = \alpha_2\left(\frac{\gamma_{x,3}}{2D}\int_{-h}^{\eta}\frac{\partial uu}{\partial x}dz + \frac{\gamma_{z,3}}{2}\frac{\partial w_\eta w_\eta}{\partial x} - \frac{\gamma_{z,3}}{2D}\int_{-h}^{\eta}\frac{\partial ww}{\partial x}dz - g\frac{\partial \eta}{\partial x}\right)$$

The two equations were summed,

$$\gamma_{t,3}\left((\alpha_1+\alpha_2)\,\alpha_{u\eta}+\alpha_1\left(\alpha_{u\eta}\frac{\partial\eta}{\partial x}-\beta_u\frac{\partial D}{\partial x}\right)\frac{\partial\eta}{\partial x}\right)\frac{\partial U}{\partial t}$$
$$=\alpha_1\left(\frac{\gamma_{x,3}\alpha_{u\eta}\alpha_{u\eta}}{2}\frac{\partial UU}{\partial x}-\left(g-\gamma_{t,3}\beta_u\frac{\partial U}{\partial x}\frac{\partial\eta}{\partial t}\right)\frac{\partial\eta}{\partial x}\right)$$
$$+\alpha_2\left(\frac{\gamma_{x,3}}{2D}\int_{-h}^{\eta}\frac{\partial uu}{\partial x}dz+\frac{\gamma_{z,3}}{2}\frac{\partial w_\eta w_\eta}{\partial x}\right)$$
$$-\left(\frac{\gamma_{z,3}}{2D}\int_{-h}^{\eta}\frac{\partial ww}{\partial x}dz-g\frac{\partial\eta}{\partial x}\right)\qquad\dots(36)$$

Equation (36) represents the final equation for calculating the horizontal depth-averaged velocity. In this research, the weighting coefficients were chosen as $\alpha_1=0.4$ and $\alpha_2=0.6$, in order to prevent the breaking wave height from becoming excessively large and to avoid overly deep breaking depths.

5.5 Differential Calculation of Vertical Velocity w.

Equation (36) contains a differential term involving vertical velocity. In this research, the differential of the vertical velocity was calculated as follows.

By integrating the continuity equation, the vertical velocity expression is obtained:

$$w_\eta=-\frac{\partial\beta_u UD}{\partial x}+u_\eta\frac{\partial\eta}{\partial x}$$

Neglecting cross-differentials and second-order differentials,

$$\frac{\partial w_\eta}{\partial x}=-\beta_u\frac{\partial D}{\partial x}\frac{\partial U}{\partial x}-\beta_u\frac{\partial U}{\partial x}\frac{\partial h}{\partial x}+\left(\alpha_{u\eta}-\beta_u\right)\frac{\partial U}{\partial x}\frac{\partial\eta}{\partial x}$$

$$\frac{\partial w_\eta w_\eta}{\partial x}=2w_\eta\frac{\partial w_\eta}{\partial x}$$

$$\frac{\partial w_\eta w_\eta}{\partial x}=2w_\eta$$
$$\left(-\beta_u\frac{\partial D}{\partial x}\frac{\partial U}{\partial x}-\beta_u\frac{\partial U}{\partial x}\frac{\partial h}{\partial x}+\left(\alpha_{u\eta}-\beta_u\right)\frac{\partial U}{\partial x}\frac{\partial\eta}{\partial x}\right)$$

Thus, the differential of the depth-averaged vertical velocity with respect to the horizontal axis-x,

$$\frac{\partial WW}{\partial x}=\frac{2w_\eta}{\alpha_{w\eta}\alpha_{w\eta}}\left(-\beta_u\frac{\partial D}{\partial x}\frac{\partial U}{\partial x}-\beta_u\frac{\partial U}{\partial x}\frac{\partial h}{\partial x}+\left(\alpha_{u\eta}-\beta_u\right)\frac{\partial U}{\partial x}\frac{\partial\eta}{\partial x}\right)\qquad\dots(37)$$

VI. NUMERICAL SOLUTION

Equations (25) and (36) were solved numerically using the Finite Difference Method for spatial derivatives and the predictor–corrector method for time derivatives. In the predictor stage, a central difference scheme was employed, while in the corrector stage, numerical integration using the Newton–Cotes method was applied. Detailed steps of the predictor–corrector procedure can be found in Hutahaean (2024a). The selection of time step δt and grid-size δx is accessible in Hutahaean (2025a).

VII. EXAMPLE OF MODEL RESULTS

This section presents several results obtained from model execution.

7.1. Wave Input

The model was provided with a sinusoidal wave input expressed by the equation,

$$\eta(0,t)=-A\cos\sigma t+A\qquad\dots(38)$$

A is the wave amplitude, $\sigma=\frac{2\pi}{T}$ is the angular frequency and T is the wave-period. This equation corresponds to the initial condition at the starting point $x=0.0$, at $t=0$, $\eta(0,0)=0.0$ and $\frac{\partial\eta}{\partial t}=0.0$. The input wave curve as a function of time t exhibits a solitary wave form, as shown in Fig. 2, for a wave period of $T=8.0\,sec.$, and wave amplitude $A=1.0\,m$.

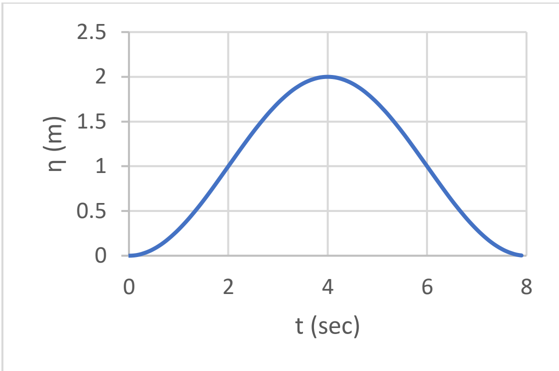

Fig (2) Input wave profile as a function of time -t.

7.2. Model Execution over a Flat Bottom.

The model was executed for five wave periods in water depth h =21.0 m, with a wave period of 8.0 s and wave amplitude 1.2 m where wave height H is 2.4 m as shown in Fig. 2 and Fig. 3.

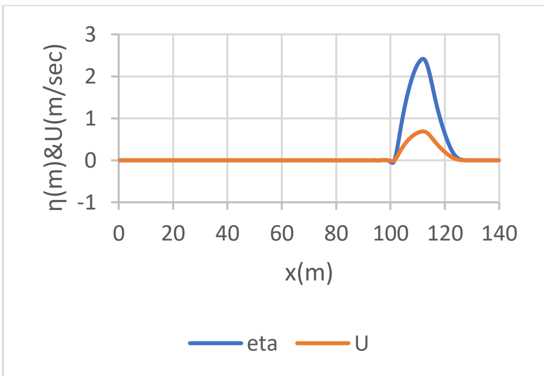

Fig (2). Wave profile after execution of 5 wave periods, $A=1.2\,m$

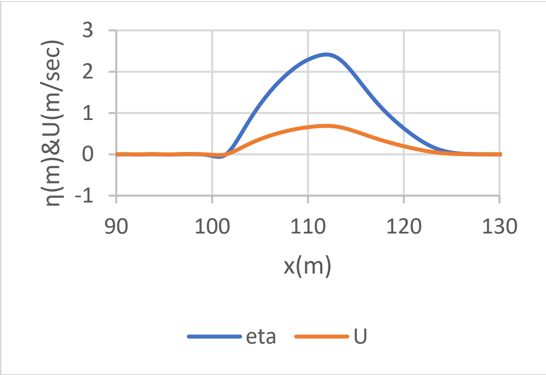

Fig (3). Detailed wave profile, wave amplitude $A = 1.2\ m$

The resulting wave profiles, shown in Fig. 2 and Fig. 3, indicate that the right-hand side of the wave is gentler than the left-hand side. The right-hand portion closely resembles a solitary wave profile, which has been widely used in previous studies. The generated wavelength is 22.0 m, with a wave steepness $\frac{H}{L} = \frac{2.4}{22} = 0.109$, which is still well below the critical wave steepness criteria from Michell (1893) $\left(\frac{H}{L}\right)_{crit} = 0.142$, and Toffoli (2010), $\left(\frac{H}{L}\right)_{crit} = 0.170$. The modeled wavelength is considerably shorter than that predicted by linear wave theory or by the Airy long-wave equation. However, the wave steepness remains well below the critical threshold.

7.3. Model Execution over a Sloping Bottom.

This section presents the results of the model execution over a sloping bottom for five different bottom slopes. The bathymetric cross-section is shown in Fig. 4. The simulated waves have a wave period of 8.0 s and a wave amplitude of 1.20 m.

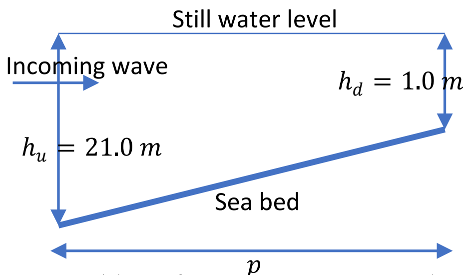

Fig (4). Bathymetric cross-section (non scale).

In Fig. 4, the deep-water depth is $h_u = 21.0\ m$ and shallow water depth $h_d = 1.0\ m$. Five values of horizontal distance p of 400 m, 300 m, 200 m, 100 m and 50 m were used, thereby 5 bottom slopes were obtained, $\frac{20}{400}, \frac{20}{300}, \frac{20}{200}, \frac{20}{100}$ and $\frac{20}{50}$.

a. Model Execution for Bottom Slope $\frac{20}{400} = 0.05$

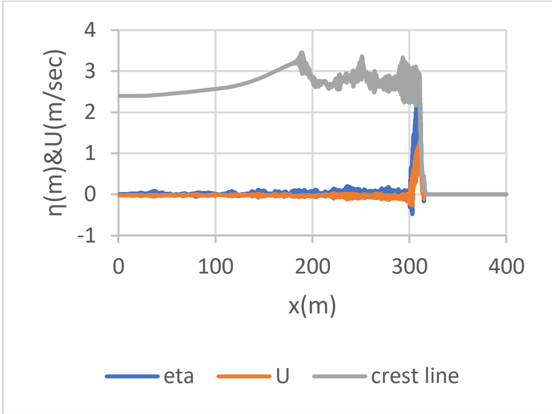

Fig (5). Shoaling and breaking over bottom slope 0.05.

In Fig. 5 and Fig. 6, the crest line represents the line connecting the wave crests. Wave breaking begins at $x = 190.0\ m$, at water depth $h = 11.5\ m$. Breaking at this point can be classified as soft breaking, characterized by the appearance of foam at the wave crest. Breaking then continues until $x = 310.5\ m$ at breaker depth $h_b = 5.48\ m$, where hard breaking occurs and the model terminates.

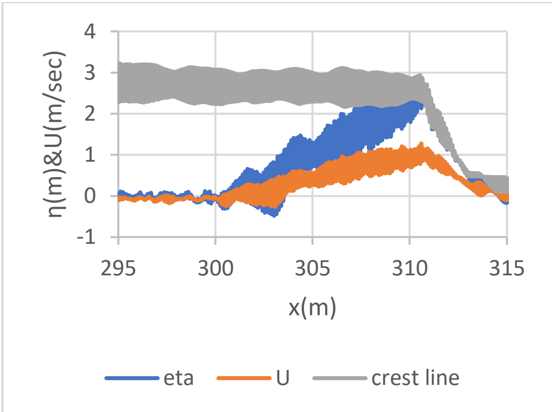

Fig (6). Breaking wave profile over bottom slope 0.05.

The parameters of the hard breaking are as follows:

$h_b = 5.48\ m$, $L_b = 16.0\ m$, $H_b = 2.60\ m$,

$\frac{H_b}{h_b} = 0.475$, $\frac{H_b}{L_b} = 0.163$

In this research, the breaking point is defined as the location where the model execution could no longer continue.

b. Bottom slope $\frac{20}{300} = 0.067$

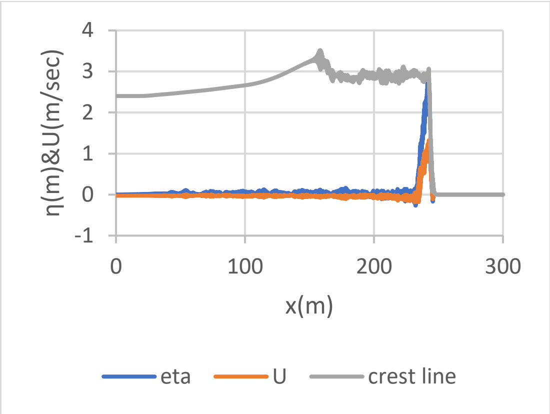

Fig (7). Shoaling breaking over bottom slope 0.067.

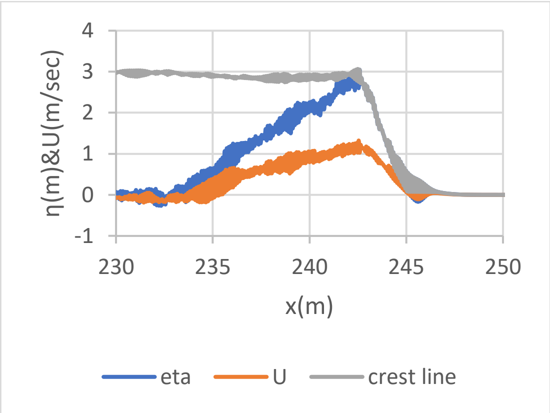

Fig (8). Breaking wave profile at bottom slope 0.067.

Parameter of breaking over bottom slope 0.067 is,

$h_b = 4.83\ m,\ L_b = 13.0\ m,\ H_b = 2.80\ m,$

$\frac{H_b}{h_b} = 0.58, \frac{H_b}{L_b} = 0.215$

c. Bottom slope $\frac{20}{200} = 0.10$

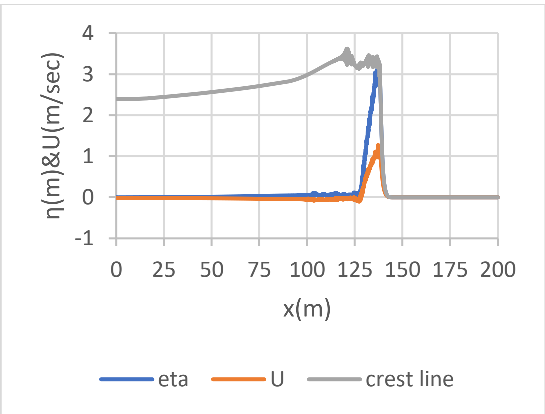

Fig (9). Shoaling breaking over bottom slope 0.10.

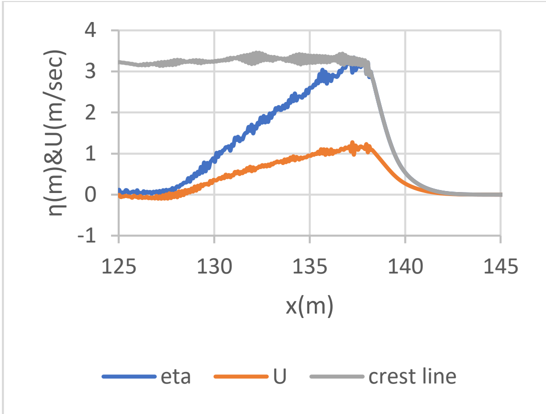

Fig (10). Breaking wave profile over bottom slope 0.1.

Parameter breaking at bottom slope 0.1 is,

$h_b = 7.25\ m,\ L_b = 15.0\ m,\ H_b = 3.20\ m,$

$\frac{H_b}{h_b} = 0.441, \frac{H_b}{L_b} = 0.213$

d. Bottom slope $\frac{20}{100} = 0.200$

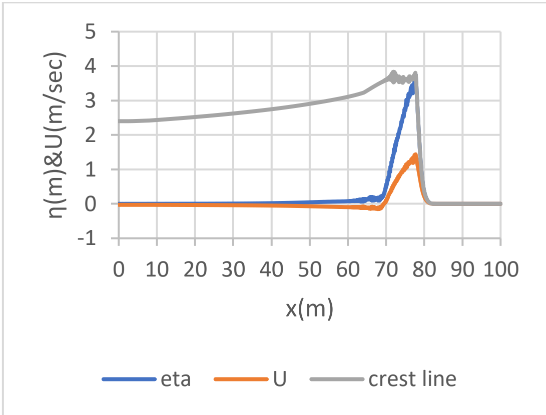

Fig (11). Shoaling breaking over bottom slope 0.200.

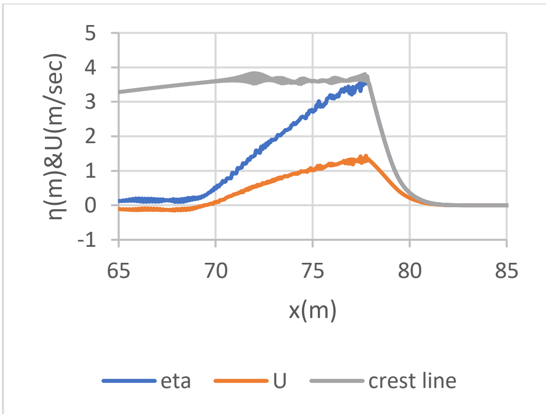

Fig (12). Breaking wave profile over bottom slope 0.200.

The breaking parameter over bottom slope 0.200 is,

$h_b = 5.44\ m,\ L_b = 13.0\ m,\ H_b = 3.60\ m,$

$\frac{H_b}{h_b} = 0.662, \frac{H_b}{L_b} = 0.277$

e. Bottom slope $\frac{20}{50} = 0.4$

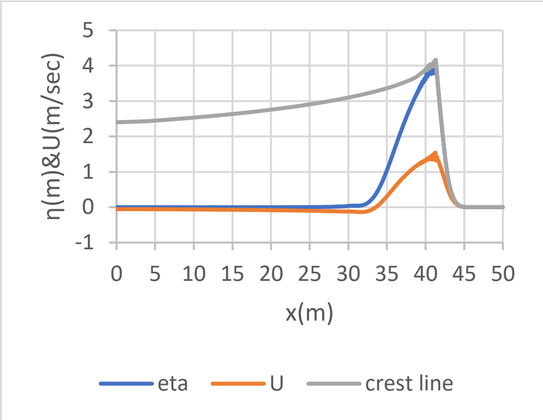

Fig (13). Shoaling breaking over bottom slope 0.4.

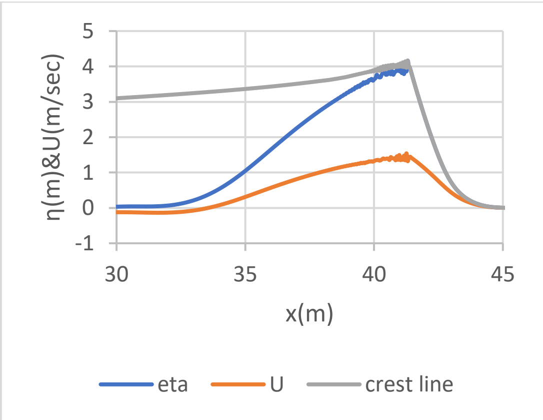

Fig (14). Breaking wave profile over bottom slope 0.4.

Parameter of breaking over bottom slope 0.4 is,

$h_b = 4.4\ m, L_b = 12.0\ m, H_b = 4.00\ m,$

$\frac{H_b}{h_b} = 0.909, \frac{H_b}{L_b} = 0.333$

Table (3). Summary of the breaking parameters

Slope	h_b (m)	L_b (m)	H_b (m)	$\frac{H_b}{h_b}$	$\frac{H_b}{L_b}$
0.050	5.48	16.0	2.6	0.475	0.162
0.067	4.83	13.0	2.8	0.579	0.215
0.100	7.25	15.0	3.2	0.441	0.213
0.200	5.44	13.0	3.6	0.662	0.277
0.400	4.40	12.0	4.0	0.909	0.333

The summary of breaking parameters is presented in Table 3. In general, it can be observed that the steeper the bottom slope, the shallower the breaker depth h_b, although deviations occur for the bottom slope of 0.10. In contrast, the breaking wave height tends to increase with increasing bottom slope.

7.4. Comparison with Previous Studies.

The influence of bottom slope on breaking parameters is well-established. Many researchers have formulated breaking index equations incorporating bottom slope as a parameter.

a.Breaking height index $\frac{H_b}{H_0}$

Several researchers have proposed relationships between the breaking wave height H_b with deep water wave height H_0 using bottom slope as the parameters as follows.

a.1.Le Mehaute and Koh (1967)

$$\frac{H_b}{H_0} = 0.76 m^{1/7} \left(\frac{H_0}{L_0}\right)^{-0.25}$$

m is the bottom slope

a.2.Sunamura and Horikawa (1974),

$$\frac{H_b}{H_0} = m^{0.2} \left(\frac{H_0}{L_0}\right)^{-0.25}$$

a.3. Ogawa and Shuto (1984)

$$\frac{H_b}{H_0} = 0.68\, m^{0.09} \left(\frac{H_0}{L_0}\right)^{-0.25}$$

The comparison between the model results and these previous studies is presented in Table 2.

Table (2) Comparison of $\frac{H_b}{H_0}$

m	$a.1$	$a.2.$	$a.3$	Model
0.05	1.395	1.319	1.258	1.083
0.067	1.478	1.354	1.311	1.167
0.1	1.603	1.404	1.389	1.333
0.2	1.841	1.494	1.534	1.5
0.4	2.115	1.591	1.694	1.667

From Table 2, it can be seen that the model results are generally close to those reported in previous studies, with the largest deviation occurring at a bottom slope of 0.05.

b. Breaking depth index $\frac{H_b}{h_b}$

Several studies have formulated relationships between breaking wave height H_b with breaking water depth h_b using bottom slope as the parameter as follows.

b.1. Collins and Weir (1969)

$$\frac{H_b}{h_b} = 0.72 + 5.6\, m$$

b.2. Sunamura (1980)

$$\frac{H_b}{h_b} = 1.1 \left(\frac{m}{\sqrt{H_0/L_0}} \right)^{1/6}$$

b.3. Larson and Kraus (1989)

$$\frac{H_b}{h_b} = 1.14 \left(\frac{m}{\sqrt{H_0/L_0}} \right)^{0.21}$$

Table (3) Comparison of values $\frac{H_b}{h_b}$

m	$b.1$	$b.2$	$b.3$	Model
0.05	0.748	0.911	0.899	0.474
0.067	0.757	0.956	0.955	0.58
0.1	0.776	1.023	1.04	0.441
0.2	0.832	1.148	1.203	0.662
0.4	0.944	1.288	1.391	0.909

From Table 3, it is evident that there are significant differences between the model results and previous studies. The common trend, however, is that the breaking depth index $\frac{H_b}{h_b}$ increases with increasing bottom slope.

c.Breaking length index $\frac{H_b}{L_b}$

Several studies have proposed relationships between breaking wave height H_b and breaking wave length L_b using bottom slope as a parameter, including:,

c.1. Ostendorf and Madsen (1979)

for $m \leq 0.1$

$$\frac{H_b}{L_b} = 0.14\, tanh \left[(0.8 + 5\, m) \frac{2\pi h_b}{L_0} \right]$$

for $m > 0.1$

$$\frac{H_b}{L_b} = 0.14\, tanh \left[\left(0.8 + 5\,(0.1)\right) \frac{2\pi h_b}{L_0} \right]$$

c.2. Rattanapitikon and Shibayama (2000)

$$\frac{H_b}{L_b} = 0.14\, tanh \left[(-11.21\, m^2 + 5.01\, m + 0.91) \frac{2\pi h_b}{L_0} \right]$$

In both equations, the parameters H_b and breaking wave depth h_b, using H_b and h_b of the model, $\frac{H_b}{L_b}$ is calculated.

Table (4). Comparison of breaking wavelength $\frac{H_b}{L_b}$.

m	c.1	c.2	model
0.05	0.179	0.137	0.162
0.067	0.174	0.133	0.215
0.1	0.179	0.14	0.22
0.2	0.167	0.135	0.277
0.4	0.131	0.068	0.333

The model's breaking wavelength cannot be directly compared with these two equations, as both are based on the critical wave steepness defined by Michell (1893) $\left(\frac{H}{L}\right)_{crit} = 0.142$. Moreover, both equations are derived from linear wave theory, which predicts wavelengths that are much longer than those observed in the model.

VIII. CONCLUSION

This research demonstrates that the developed governing equations, the water surface elevation equation and the horizontal water particle velocity equation, effectively model wave shoaling and breaking processes. The results indicate that both equations capture the essential dynamics of wave transformation, including the evolution of wave height, depth, and horizontal particle motion.

The use of a solitary wave input profile ensures consistency with the initial conditions at the input point, allowing the Kinematic Free Surface Boundary Condition to be applied without difficulty. This enables accurate computation of vertical water velocity and its derivatives across all spatial points. Vertical velocity is a key factor in determining horizontal water particle velocity, as it provides the necessary energy for horizontal motion. For further refinement, a mechanism for wave energy dissipation during hard breaking should be incorporated into both the water surface elevation equation and the horizontal velocity equation.

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International Journal of Advanced Engineering Research and Science (IJAERS)
Peer-Reviewed Journal
ISSN: 2349-6495(P) | 2456-1908(O)
Vol-12, Issue-10; Oct, 2025
Journal Home Page Available: https://ijaers.com/
Article DOI: https://dx.doi.org/10.22161/ijaers.1210.3

Surface analysis of bovine teeth submitted to dental bleaching: in vitro study

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Received: 11 Sep 2025,

Received in revised form: 09 Oct 2025,

Accepted: 13 Oct 2025,

Available online: 17 Oct 2025

***Keywords*— Tooth whitening, Bleaching agents, Hydrogen peroxide, pH analysis, Bovine teeth**

***Abstract*—*Tooth whitening is a procedure that lightens the color of a tooth by applying a chemical agent to oxidize the organic pigmentation of the tooth. The agents hydrogen peroxide and carbamide peroxide are oxidizing agents, which, after diffusion, dissociate to produce free radicals that affect pigmented organic molecules. Objective: To evaluate the action of bleaching agents on the dental surface of bovine teeth. Through an in vitro laboratory experiment, the action of bleaching agents (Whiteness HP 35% - FGM and Potenza Bianco Pro 35% - PHS) on the tooth surface was evaluated, from which 30 bovine teeth were collected, sanitized with distilled water, stored in saliva for seven days, cut by separating the root from the crown with a standardized 10x10 mm cut in the straight piece with a diamond disc, then immersed in saliva for another seven days, where they were divided into three groups (samples), defined in control group (GC), test groups I and II (GT I and TG II). Prophylaxis was performed on all teeth in the groups (samples) with prophylactic paste and a straight Robinson brush. Subsequently, the teeth in the control group (CG) were immersed again in artificial saliva for another seven days. After seven days, the pH of the two bleaching agents was descriptively analyzed, and the analysis of free energy/wetting of the groups (samples) was also carried out. The pH of Potenza Bianco Pro 35% bleach was 6.0 and its wettability was 119.85. The pH of Whiteness HP 35% bleach was 8.5 and its wettability value was 119.66. The bleaching agent Potenza Bianco Pro – PHS is more acidic and the Whiteness HP – FGM is alkaline. The wettability of the whitening agent Potenza Bianco Pro – PHS is similar to Whiteness HP – FGM > 90°.*

I. INTRODUCTION

Teeth are an integral part of facial aesthetics and are involved in complex social, cultural, and psychological interactions. It is commonly perceived that whiter teeth enhance the beauty of a person's smile. As a result, the demand for whiter and brighter teeth is increasing among today's patients. Teeth whitening is one of the fastest-growing areas in aesthetic and restorative dentistry. In light of this, there is a need to delve deeper into understanding how the dental surface behaves during the action of whitening agents[1].

Tooth aesthetics and color are important topics for society. This includes both dental professionals who aim to select the correct tooth shade and restorative material, and patients who wish to improve the appearance of their smile. Tooth color is influenced by a combination of its intrinsic shade and the presence of any extrinsic stains that may form on the tooth surface[2].

Whitening is a procedure that involves lightening the color of a tooth through the application of a chemical agent that oxidizes organic pigmentation in the tooth. Teeth are whitened by materials such as hydrogen peroxide (HP) and carbamide peroxide (CP), which diffuse initially through the enamel and dentin. These oxidizing agents, after diffusing, dissociate to produce free radicals that target pigmented organic molecules, reducing light absorption and creating a "whitening effect[1].

It is extremely important to evaluate the action of whitening agents on the dental surface through an in vitro study. The scope of this study was to evaluate the effects of whitening agents on the dental surface of bovine teeth.

II. METHODS

Thirty bovine teeth (n=30) were collected as a convenience sample from a slaughterhouse in the city of Teresina, PI, with authorization from the Animal Use Ethics Committee of Centro Universitário Santo Agostinho (CEUA/UNIFSA), under protocol no. 6064/22. Since biological material was involved, the study was conducted in accordance with Resolution No. 003/2015 and the appointment ordinance No. 007/2015, which aim to enforce the provisions of Law No. 11.794 of October 8, 2008, and other applicable regulations regarding the use of animals in teaching and research, especially the resolutions of the National Council for the Control of Animal Experimentation (CONCEA).

After extraction, the teeth were thoroughly washed with distilled water and immersed in 500 mL of artificial saliva (1% CMC; 0.12% potassium chloride; 0.0052% magnesium chloride; 0.0084% sodium chloride; 3% sorbitol; 3% monobasic potassium phosphate; 0.0146% calcium chloride; q.s.p. distilled water to 1000 mL) for seven days. Next, the crowns were separated from the roots using diamond discs (American Burrs) attached to a straight handpiece with a micromotor (KaVo), making standardized cuts of 10x10 mm, measured with a millimeter ruler for identification. The samples were cleaned and stored in containers submerged in artificial saliva for another seven days, after which they were divided into three groups (samples), with n=10 in each group: control group (CG), and test groups I and II (TG I and TG II).

Prophylaxis was performed on all sample teeth using Shine prophylactic paste (tutti-frutti flavor) – Maquira and a straight Robinson brush – Preven, attached to a low-speed contra-angle handpiece with a KaVo micromotor. The control group (CG) teeth were then re-immersed in artificial saliva for an additional seven days. The hydrogen peroxide and thickening agents from both whitening products (Whiteness HP 35% – FGM and Potenza Bianco Pro 35% – PHS) were mixed using the mixing tray and spatula included in the kit, in a 3:1 drop ratio, according to each manufacturer's instructions.

The pH of the two whitening agents was analyzed descriptively using universal pH strips – KASVI. Following this, the physicochemical properties of the enamel surface were characterized by contact angle measurements using the sessile drop method to determine surface free energy. A fixed-volume automatic pipette – Kacil was used to dispense 0.5 µL of each liquid onto the enamel surface of each bovine tooth fragment using a 0.5 mm gauge needle.

Images were captured using a Canon Rebel T5i camera with a 100 mm macro lens.After seven days, additional images of the control group (CG) were taken with distilled water applied to the dental surface to analyze surface free energy/wettability. Once the laboratory phase was completed, the images were processed using Surftens 4.7 Automatic software (OEG GmbH, Frankfurt, Oder, Germany), where settings were configured for “distilled water” and “4-point analysis.” In the software, the image was opened, zoomed in, and centered. Then, four (4) points were marked: the first exactly at the intersection between the specimen surface and the drop; the second and third at two random points on the drop’s surface; and finally, the fourth at the opposite point of intersection between the drop and the specimen surface[3]. After marking the last point, the software automatically calculated the contact angle and displayed the result.

Statistical

Each image was analyzed in triplicate by two researchers. Finally, the collected data were presented as means ± standard error of the mean and subjected to statistical testing using GraphPad Prism software.

III. RESULTS

The Potenza Bianco Pro 35% whitening agent exhibited an acidic pH, whereas the Whiteness HP 35% whitening gel showed an alkaline pH (Table 1).

Table 1. Descriptive data of the pH of the tested substances.

	Distilled water	Potenza bianco Pro35%	Whiteness hp 35%
pH	7,0	6,0	8,5

Source: Authors (2025).

There was no statistically significant difference ($p > 0.05$) between the control group and the tested whitening agents in terms of contact angle/wettability. The comparisons between the groups are listed in Table 2.

Table 2. Means (standard deviations) of the wettability of the whitening agents.

	Distilled Water (GC)	Potenza Bianco Pro35%(GTI)	Whiteness HP 35% (GT II)
CONTACT ANGLE	92,47± (0,66) A	119,85 ± (2,17) A	119,66± (0,29) A

Means followed by the same uppercase letters indicate no statistically significant difference in the rows(p>0.05). Source: Authors (2025).

This study evaluated the effects of whitening agents on the surface of bovine teeth. The pH of the Potenza Bianco Pro 35% whitening agent was acidic, whereas the pH of the Whiteness HP 35% whitening agent was alkaline. Furthermore, the mean wettability values showed no statistically significant difference between the two test groups. Thus, the null hypothesis that whitening agents do not act equally on the dental surface is confirmed by the pH test. However, both whitening agents studied exhibited similar wettability values on the dental surface.

Dentists use high-concentration whitening gels due to their intense color change in the initial applications. Because the free radicals generated are not only selective to chromophores, but also interact with dental structures during diffusion, they can cause tooth sensitivity both during and after the procedure.

The application of whitening gels with acidic pH causes tooth sensitivity, which leads to the recommendation of whitening agents with neutral or alkaline pH. Therefore, the whitening agent in test group I (Whiteness HP 35% – FGM) is the most suitable for whitening treatments, as its alkaline pH reduces adverse effects related to sensitivity caused by other agents available on the market. As more products are introduced, the focus has been primarily on the overall impact of whitening agents on enamel surface morphology and mechanical action, rather than the contribution of peroxide pH to initiating a destructive chain reaction during the whitening process [4].

According to laboratory studies, enamel exposed to whitening products with different pH levels shows an increased risk of demineralization and root resorption after prolonged exposure to highly acidic products with pH values below 5.2 or highly basic products [5].

Thus, when evaluating the agents used in this study through the pH test, it was found that the GT I agent had a pH close to 5.2, corroborating the occurrence of adverse effects such as sensitivity and demineralization of the tooth surface. The most common adverse effect of most peroxide-based whitening procedures is tooth sensitivity, and efforts have been made to overcome the sensitivity caused by whitening treatments. As a result, fluoride, potassium nitrate, amorphous calcium phosphate (ACP), or hydroxyapatite nanoparticles (n-HAP) have been introduced into whitening agents to reduce the occurrence of hypersensitivity or demineralization [6].

However, even when using a desensitizing agent, it is still necessary to have pH-neutral or alkaline products available on the market in order to minimize the side effects of whitening treatment, such as post-whitening sensitivity, as presented by Whiteness HP 35%. Wettability was defined as the ability of a liquid to wet a solid. This can be exemplified as a drop of liquid resting on a solid surface, on which the liquid may or may not spread. Water, being a polar liquid, tends to spread over a surface with high surface energy and lead to the formation of a drop in areas with low energy. The analysis of the contact angle of a sessile drop, demonstrated by the angle of the section of the drop of a liquid material on a surface in equilibrium, is a means of quantifying this behavior [7].

The degree of spreading in which the fluid droplet flows over the solid surface is called wetting. The formation between the droplet-sphere and the substrate plane is the contact angle, which is consequently the measure of wetting. If the angle is small, wetting is considered good; when the angle is greater than 90 degrees, wetting is considered poor. When there is strong attraction between the molecules of the substance and the solid, this means good wetting, and surface energy also influences this attraction [8].

Given this, the variable investigated was similar for the two whitening agents under study and, in addition, showed poor results, since they presented an angle > 90º. Although the samples were prepared rigorously and following the entire pre-established laboratory sequence, the experimental results obtained in this in vitro study still need to be confirmed in future clinical investigations on the surface of human teeth, since the present study evaluated the action of whitening agents on the surface of bovine teeth.

IV. CONCLUSION

- The Potenza Bianco Pro -PHS whitening agent is acidic, while Whiteness HP -FGM is alkaline;

- The wettability of the Potenza Bianco Pro - PHS whitening agent is similar to that of Whiteness HP - FGM > 90º.

DATA AVAILABILITY STATEMENT

The authors confirm that all data generated or analyzed during this review are included in this article.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no financial conflicts.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to the Santo Agostinho University Center for the institutional support provided throughout the completion of this work. The infrastructure offered, access to academic resources, and the environment conducive to research were fundamental to the development of this article.

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International Journal of Advanced Engineering Research and Science (IJAERS)
Peer-Reviewed Journal
ISSN: 2349-6495(P) | 2456-1908(O)
Vol-12, Issue-10; Oct, 2025
Journal Home Page Available: https://ijaers.com/
Article DOI: https://dx.doi.org/10.22161/ijaers.1210.4

Cervical cancer from screening to treatment: A snapshot of reality

Câncer de colo uterino do rastreio ao tratamento: Um retrato da realidade

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Received: 09 Sep 2025,
Received in revised form: 10 Oct 2025,
Accepted: 16 Oct 2025,
Available online: 19 Oct 2025

***Keywords*— Cervical cancer, Epidemiology, Prognosis, Screening program.**

***Palavras-chave*— Câncer de colo de útero, Epidemiologiz, Prognóstico, Programa de rastreamento.**

Abstract*—Cervical cancer is a major public health problem, being the third most common neoplasm in women in Brazil, according to INCA (2022). An ecological study carried out between 2013 and 2022 with data from SIH-SUS, SIM, SISCOLO and SISCAN analyzed the epidemiological profile of the disease, where cervical cancer was the 5th most recurrent between 2013 and 2022, with 24,599 deaths, representing 12.12% of cancer deaths, behind only breast and lung cancer. The study also revealed that the Northeast had the highest number of preventive screening exams, followed by the South. In addition, the increase in cervical cancer cases accompanies advancing age, with the highest peak between 40 and 49 years of age (24.59%). The high mortality from cervical cancer is associated with the significant number of abnormal results in preventive exams. These data highlight the need for more effective and specific intervention measures, considering the social and cultural characteristics of the affected populations. Raising awareness of the importance of screening is essential to reduce the incidence and mortality from the disease.*

***Resumo*—** *O câncer de colo de útero é um importante problema de saúde pública, sendo o terceiro mais comum entre as neoplasias em mulheres no Brasil, segundo o INCA (2022). Um estudo ecológico realizado entre 2013 e 2022 com dados do SIH-SUS, SIM, SISCOLO e SISCAN analisou o perfil epidemiológico da doença, onde o câncer de colo de útero foi a 5ª mais recorrente entre 2013 e 2022, com 24.599 óbitos, representando 12,12%*

das mortes por câncer, ficando atrás apenas do câncer de mama e de pulmão. O estudo também revelou que o Nordeste apresentou o maior número de exames preventivos por rastreamento, seguidos pelo Sul. Além disso, o aumento dos casos de câncer de colo de útero acompanha o avanço da idade, com maior pico entre 40 e 49 anos (24,59%). A alta mortalidade por câncer de colo de útero está associada ao número significativo de resultados anormais nos exames preventivos. Esses dados destacam a necessidade de medidas de intervenção mais eficazes e específicas, considerando as características sociais e culturais das populações afetadas. A conscientização sobre a importância do rastreamento é fundamental para reduzir a incidência e a mortalidade pela doença.

I. INTRODUÇÃO

O câncer de colo de útero (CCU) ou câncer cervical é um problema de saúde pública global que acomete uma quantidade significativa de mulheres. De acordo com o Instituto Nacional de Câncer - INCA (2022), ele está entre os mais incidentes, além de ser o terceiro depois do câncer de pele não melanoma (SILVEIRA, 2022). O CCU é caracterizado como uma neoplasia maligna de replicação desordenada do epitélio de revestimento do colo do útero e que acomete seu tecido subjacente, o estroma (SILVA, 2020).

Neste sentido, existem fatores ambientais e genéticos que favorecem o aparecimento deste, como é o caso da infecção persistente pelos tipos oncogênicos do papilomavírus humano (HPV), é um fator determinante para o surgimento desse câncer, sendo os tipos 16 e 18 são responsáveis pela maioria dos casos (SILVA, 2020). Contudo, é válido salientar que, dentre todos os tipos de câncer, o CCU é o que apresenta um dos mais altos potenciais de prevenção e cura, pois apresenta etapas bem definidas, longo período para evolução das lesões precursoras e facilidade de detecção das alterações na fase inicial (FONSECA, 2022).

A prevenção primária se dá por meio da utilização de preservativo durante as relações sexuais, considerando que a realização de sexo protegido é uma das maneiras de prevenir a contaminação pelo HPV, além da vacinação, que está disponível em todo o território nacional para meninas entre 9 a 14 anos e meninos de 11 a 14 anos, a qual apresenta alta eficiência na indução da produção de anticorpos específicos, sendo os tipos virais 6, 11, 16 e 18 (DE SOUSA, 2021).

A prevenção secundária é feita por meio do exame citopatológico cervical, conhecido popularmente como "Papanicolau" ou preventivo, e é uma das principais estratégias para detecção precoce das lesões uterinas, e por conseguinte, favorecendo um bom prognóstico. Esse exame tem como população alvo mulheres com idade entre 25 e 64 anos, que possuam colo do útero e que já tenham iniciado sua vida sexual (LOPES, 2019). A recomendação para rastreamento nessa faixa etária é anual, e se houver 2 exames consecutivos negativos, o intervalo de realização passa a ser trienal. Já para mulheres com mais 64 anos e que nunca se submeteram ao exame citopatológico, deve-se realizar 2 exames com intervalo de 1 a 3 anos e, se ambos forem negativos, essas mulheres podem ser dispensadas de exames adicionais (DA SILVA, 2022).

Ademais, a biópsia cervical em cone é usada para diagnosticar lesões endocervicais ocultas em situações como: má visualização da junção escamo colunar (JEC) na colposcopia, extensão do epitélio com displasia de alto grau para o canal endocervical, achado citológico sugestivo de displasia ou carcinoma in situ (GUIMARÃES, 2019).

Atualmente, o tratamento do câncer de colo uterino é ditado pela International Federation of Gynecology and Obstetrics (FIGO), havendo três possibilidades, sendo elas: cirurgia, quimioterapia e radioterapia. O tipo de conduta dependerá do estadiamento da doença, tamanho do tumor e fatores pessoais, como a idade e desejo de ter filhos (CERQUEIRA, 2023). A terapêutica apropriada das lesões precursoras (lesões intraepiteliais escamosas de alto grau na citologia, neoplasias intraepiteliais cervicais na histologia e adenocarcinoma in situ) é meta prioritária para a redução da incidência e mortalidade pelo câncer do colo uterino (DA SILVA, 2022).

Por fim, o CCU se caracteriza como uma problemática multifacetada e uma doença que dispõe de tecnologia barata e de fácil utilização para o diagnóstico e tratamento precoce, sendo as mortes causadas por essa patologia muitas vezes consideradas evitáveis, dada as incontestáveis evidencias de que é um dos tipos de câncer de mais fácil prevenção e tratamento eficaz, se detectado precocemente (NUNES, 2020). Desse modo, o mapeamento dos principais fatores associados a sua ocorrência e a determinação do perfil epidemiológico da população diagnosticada são de extrema importância, para a compreensão do seu acometimento e que medidas sejam tomadas pelo Sistema Único de Saúde (SUS) para conscientização da população feminina sobre a importância dos exames preventivos.

II. MATERIAL E MÉTODO

Trata-se de um estudo epidemiológico, transversal, descritivo, de caráter quantitativo, que realiza uma análise histórica do perfil epidemiológico do rastreio ao tratamento do câncer de colo de útero em mulheres adultas no Brasil e suas regiões, no período de 2013 até 2022, sendo incluídas no estudo mulheres na faixa etária acima de 19 anos.

Utilizou-se como fonte de dados para consulta o Sistema de Informações Hospitalares do SUS (SIH/SUS), Sistema de Informação sobre Mortalidade (SIM), Sistema de Informação do Câncer de Colo de Útero (SISCOLO) versão 4.0/superior, Sistema de Informação do Câncer de colo do útero e mama (SISCAN) e o Painel de Oncologia, disponibilizados pelo Departamento de Informática do Sistema Único de Saúde (DATASUS), no endereço eletrônico http://www.datasus.gov.br. Os dados dessas plataformas foram coletados a partir de informações do ano da ocorrência, região, faixa etária, cor/raça, mortalidade, último preventivo, motivo do exame, procedimento, ano do diagnóstico, estadiamento, modalidade terapêutica e tempo de tratamento detalhado.

Os dados coletados foram tabulados no programa Microsoft Office Excel, para que, através das fórmulas preconizadas na literatura, fosse realizada a análise epidemiológica. Desse modo, os resultados obtidos são apresentados através de tabelas, quadros e gráficos. Posteriormente, haverá a interpretação dos dados estabelecidos e discussão, a partir do embasamento teórico, acerca da temática.

Ademais, utilizou-se como ferramentas norteadoras da revisão bibliográfica as bases de dados National Library of Medicine (PubMed) e Literatura LatinoAmericana e do Caribe em Ciências da Saúde (LILACS). Assim, para seleção dos artigos foram utilizados os seguintes Descritores em Ciência da Saúde (DeCS): Neoplasia do Colo do Útero, Epidemiologia e Citologia.

III. RESULTADOS E DISCUSSÃO

Ao observar a morbidade dos cânceres na população feminina na plataforma do SIH-SUS (dados de 2023), dentre os anos de 2013 e 2022, observa-se que o câncer de colo de útero é o 5ª mais recorrente no período, dentre as 33 apresentadas na plataforma, constando como 221.683 mulheres de 3.568.475, equivalente a 6,21% das ocorrências do período. Por outro lado, quando observados os óbitos por neoplasias encontramos o câncer de colo de útero em 3º lugar, constando 24.599 de 202.882, equivalente a 12,12%, ficando atrás apenas do câncer de mama e câncer de traquéia, brônquios e pulmão, respectivamente.

No tocante à ocorrência de câncer de colo de útero quando relacionada à cor/raça, a população parda é a mais acometida (42,1%), seguida da branca (36,58%). Quando analisadas sobre o Carcinoma in situ de colo de útero, a mais prevalente é a população branca (44,4%) e em seguida as mulheres pardas (32,5%).

Ao analisar a mortalidade por região causada por câncer do colo do útero na plataforma SIM-SUS entre os anos de 2013 e 2021, é possível estabelecer que o intervalo etário mais afetado foi o de 50-59 anos com total de 12.017 mortes, totalizando 21,77%. Logo, é possível observar que tanto o diagnóstico de câncer do colo do útero quanto o carcinoma in situ de colo do útero podem ser realizados em mulheres dentro da faixa etária de 35 e 44 anos, mas, geralmente a idade média no momento do diagnóstico é aos 50 anos. O câncer do colo uterino dificilmente vai evoluir em mulheres com idade inferior aos 20 anos. A maioria das mulheres mais velhas desconhece o risco do câncer à medida que envelhecem. Em torno de vinte por cento dos casos de câncer têm sido diagnosticados em mulheres que têm 65 anos de idade. Contudo, o CCU dificilmente ocorre em mulheres que efetuam o rastreamento para o CCU regularmente antes dos 65 anos.

Em relação ao exame anatomopatológico do colo do útero, os dados foram colhidos na plataforma SISCOLO-SUS relacionando a região em que o exame foi coletado com o resultado. Ainda há uma grande quantidade de resultados anormais, como é possível verificar no Anexo Gráfico 3, principalmente na região Norte, apresentando 2.015, equivalente a 87,19% dos resultados. Em segundo lugar, vem a região Sul com 4076 testes anormais de 4891 testes feitos no período citado, equivalente a 83,36%. No entanto, o número de mortes pelo câncer de colo do útero reduziu expressivamente com a ampliação do rastreamento da doença por meio do exame de Papanicolaou, mesmo que nos últimos dez anos não tenha ocorrido diminuições significativas (INCA, 2023). O perfil socioeconômico e cultural do país é mais uma das limitações que estabelecem aspectos relevantes, que explicam a continuidade da incidência, ocasionando a mortalidade pelo CCU em algumas regiões do Brasil. A situação de baixo nível socioeconômico nas regiões Norte e Nordeste, influenciam no alcance aos serviços de rastreamento para prevenção e tratamento em tempo favorável à cura.

O câncer de colo de útero encontra-se como segundo câncer mais prevalente nas mulheres e, de acordo com o INCA (2020), observou-se que a cada ano do triênio em 2020/2022, o diagnóstico de novos casos no Brasil foi representado por 16.559 e a região com mais incidência realmente foi o Nordeste, com uma taxa de 16,10/100 mil habitantes. Desta forma, em se tratando do número de exames realizados nas regiões do nordeste, principalmente entre 2015-2019, foram observados 16.952.217 exames citológicos, tendo também uma cobertura simultânea de 5.172.360 exames realizados. (DA SILVA, 2022)

No que se refere aos exames por margens cirúrgicas segundo o ano do resultado, de acordo com a plataforma SISCAN (dados de 2023), dentre os anos de 2013 e 2022, nota-se que as margens que se destacam foram as comprometidas, principalmente no ano de 2020 com 2.917 de 31.587 (equivalente a 9,23%), seguido do ano de 2022, com 3.365 de 44.330 (7,59%). Ao compararmos com os demais tipos de exames, ainda é notório que em todos os anos pesquisados tiveram altas porcentagens de ignorados, sendo equivalente a 218.535 de um total de 340.888 (64,11%).

No Brasil, quando suspeita-se de câncer de colo de útero, é importante que a paciente realize o exame histopatológico e, a depender do resultado, avalia-se como vai ser o seguimento. Dessa forma, percebe-se o predomínio dos casos com as margens comprometidas e, com isso, devem ser realizados acompanhamento após 4 meses da conização, diferente das com margens livres que é recomendado apenas com 6 meses. Assim sendo, essa avaliação deve ser realizada por meio da citologia oncótica, colposcopia e, se necessário, a biópsia cervical (DOS SANTOS, 2020).

Em se tratando de exames por tipo de procedimento cirúrgico segundo o ano resultado, pela plataforma SISCAN (dados de 2023), dentre os anos de 2013 e 2022, observa-se na Anexo 2, que houve um considerável destaque em relação aos exames com biópsia, sendo maior no ano de 2013, representado por 1.225 de 1.254 (97,68%), seguido do ano de 2014, com 21.766 de 23.984 (90,75%). O ano de 2020 foi o que apresentou menor número, com 25.590 de 31.587 (81,01%).

De acordo com as Diretrizes Brasileiras do Rastreamento do Câncer do Colo do Útero, quando um exame de rastreamento está alterado, devem ser realizados ou o exame citopatológico ou a colposcopia, com o objetivo de confirmação diagnóstica. Em relação a biópsia ou excisão da lesão, esta é considerada padrão ouro e geralmente é realizada após a avaliação colposcópica, que, por sua vez, confirma o diagnóstico mediante a análise histopatológica do material coletado, de forma a fundamentar a conduta clínica do tratamento. Porém, ainda revela-se certa dificuldade quanto à abordagem realizada pela biópsia, de tal forma que o número realizado vem sendo diminuído e, consequentemente, não há notificação dos diagnósticos quando positivos para a CCU (CLARO, 2022).

O início precoce das relações sexuais aumenta o risco do CCU e essa relação é plausível porque a zona transformada do epitélio cervical é mais proliferativa durante a puberdade e a adolescência (período frágil) bem como principalmente suscetível a alterações causadas por agentes transmissores, principalmente o HPV. Durante a adolescência essa infecção viral tem maior probabilidade de se tornar um processo crônico, o que significa maior risco de câncer de colo de útero. Ao mesmo tempo, programas de atenção específicos para adolescentes precisam ser implementados para reduzir a progressão das lesões precursoras de colo de útero (REZENDE, 2023). Por requerer anos de desenvolvimento, é considerada rara em mulheres com menos de 30 anos e sua incidência aumenta gradativamente até atingir o pico na faixa de 45 a 50 anos.

Ao analisar as modalidades terapêuticas, em cada região do país, na população feminina na plataforma Painel onco, entre os anos de 2013 e 2022, observa-se que há uma predominância para a realização da radioterapia, quando comparada à cirurgia e quimioterapia, correspondendo a 106.360 (73,28%), de um total de 145.136 pacientes, podendo estar ou não associada com quimioterapia e/ou cirurgia. Foi observado que no Sudeste há uma maior incidência de tratamentos, correspondendo a 50.249 pacientes (34,62%), seguida pelo Nordeste com 42.392 pacientes (29,21%), desses a radioterapia está presente no tratamento de 18.518 e 18.825 pacientes, respectivamente. Já o Centro-Oeste obteve um menor número de tratamentos, correspondendo a 10.966 (7,55%) do total.

As taxas de incidência e o número de casos novos de câncer estimados são importantes para avaliar a magnitude da doença no território e programar ações locais (INCA, 2022). O maior número de casos novos estimados de câncer do colo do útero é observado para as regiões Sudeste e Nordeste, que são as regiões mais populosas do Brasil. Entretanto, quando avaliadas as taxas de incidência observamos as maiores taxas na região Norte.

IV. CONCLUSÃO

O câncer do colo uterino é um desafio à saúde pública, havendo necessidade de fortalecimento nas ações de prevenção da doença, promoção da saúde e controle do acometimento pelo CCU, a fim de diminuir sua mortalidade e proporcionar uma qualidade de vida para as mulheres brasileiras.

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International Journal of Advanced Engineering Research and Science (IJAERS)
Peer-Reviewed Journal
ISSN: 2349-6495(P) | 2456-1908(O)
Vol-12, Issue-10; Oct, 2025
Journal Home Page Available: https://ijaers.com/
Article DOI: https://dx.doi.org/10.22161/ijaers.1210.5

Artificial Intelligence and Smart Technologies for Sustainable Civil Engineering

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Received: 23 Sep 2025,
Received in revised form: 18 Oct 2025,
Accepted: 22 Oct 2025,
Available online: 25 Oct 2025

***Keywords*— Artificial Intelligence, IoT, Sustainable Construction, Machine Learning, Fuzzy Logic, Seismic Automation, Industry 5.0, Smart Cities.**

***Abstract*—Civil engineering is experiencing a paradigm shift driven by artificial intelligence (AI), the Internet of Things (IoT), automation, and sustainable practices. Across multiple studies, AI has been shown to optimize material design, enhance monitoring systems, and support resilient infrastructure. Machine learning models accurately predict compressive strength and embodied carbon of eco-friendly concrete, while Artificial Intelligence based life cycle analysis improves the sustainability assessment of geopolymer concretes. Complementary research highlights quarry dust and industrial by-products as viable substitutes for natural resources, promoting low carbon construction. In structural health monitoring, edge-AI frameworks enable real-time crack detection in bridges, enhancing safety and reducing latency. Generative AI integrated with Building Information Modeling (BIM) introduces automated structural design pipelines, producing diverse and regulation-compliant solutions. Internet of Things systems play a pivotal role in smart cities, enabling real-time management of energy, transportation, and utilities, while seismic automation platforms like RAPID-SIS accelerate disaster response through automated accelerograph data processing. Fuzzy logic strengthens decision-making in uncertain transportation systems, offering reliable solutions for congestion, safety, and autonomous vehicle control. At the industrial scale, Industry 5.0 approaches such as AI powered virtual assistants in concrete plants demonstrate improved efficiency, reduced human error, and sustainable operations. Collectively, these innovations illustrate a convergence of digital transformation and ecological responsibility, providing a framework for developing resilient, sustainable, and smart infrastructure. By integrating advanced digital tools, eco-friendly materials, and human–machine collaboration, civil engineering is poised to meet the challenges of climate change, rapid urbanization and resource scarcity while aligning with global sustainability goals.*

I. INTRODUCTION

Civil engineering stands at the threshold of a transformative era shaped by rapid urbanization, climate change, and increasing demands for sustainable infrastructure. Conventional approaches that once relied heavily on manual processes, empirical testing, and resource intensive construction are no longer sufficient to meet these challenges. Instead, the discipline is embracing digital transformation, automation, and environmentally conscious practices. Emerging technologies including Artificial Intelligence (AI), the Internet of Things (IoT), fuzzy logic, seismic automation, and Industry 5.0 are revolutionizing how infrastructure is designed, monitored, and managed. Collectively, these advancements provide opportunities to create resilient, low carbon, and smart infrastructure that aligns with global sustainability goals. One of the most pressing concerns in modern construction is the high carbon footprint of concrete, primarily due to the use of Ordinary Portland Cement (OPC). Research on eco-friendly concrete design highlights that replacing OPC with supplementary cementitious materials (SCMs) such as fly ash, slag, and quarry dust can significantly reduce emissions. However, predicting the mechanical performance and durability of these new mixes is complex. Studies applying machine learning (ML) have shown remarkable accuracy in forecasting compressive strength, workability, and embodied carbon. Models such as Gradient Boosting and Random Forest have demonstrated predictive capabilities that not only accelerate mix design but also provide actionable pathways for decarbonisation. Reviews of geopolymer concrete further extend this scope by demonstrating how AI based life cycle analysis (LCA) tools can assess sustainability across environmental, social, and economic dimensions, ensuring comprehensive evaluations of new construction materials. Beyond material innovation, AI is also advancing the structural health monitoring (SHM) of infrastructure. Conventional inspection methods for bridges and critical structures are labor-intensive and prone to delays. Edge AI frameworks now enable real time crack detection, reducing latency and enhancing safety by bringing decision making closer to the source of data. In parallel, Generative AI combined with Building Information Modeling (BIM) has introduced automated design pipelines capable of producing diverse, regulation compliant structural models. Such approaches not only accelerate design processes but also enhance adaptability, making them vital for future proof infrastructure development.

The role of IoT technologies in smart cities is equally significant. By connecting transportation systems, energy grids, and urban utilities, IoT provides real-time insights that improve efficiency, reduce waste, and enhance service delivery. For instance, adaptive traffic management systems use sensor data to reduce congestion, while smart grids optimize energy distribution. Complementing this, seismic automation platforms like RAPID-SIS provide instant accelerograph data processing, enabling engineers and disaster management authorities to make rapid, evidence-based decisions after seismic events. This automation reduces human error and accelerates emergency response, strengthening resilience in earthquake prone regions. Transportation systems, which are inherently uncertain and dynamic, benefit from fuzzy logic approaches that mimic human reasoning. Research demonstrates how fuzzy models can forecast traffic flow, optimize logistics, and improve accident prediction. With the increasing adoption of autonomous vehicles and the growing complexity of global supply chains, such adaptive decision-making systems are crucial for ensuring efficiency and safety in modern mobility. At the industrial scale, the integration of Industry 5.0 principles emphasizes collaboration between human expertise and intelligent systems. In the concrete industry, AI powered virtual assistants are being developed to support production, reduce operational errors, and enhance sustainability. These assistants exemplify the transition from automation-driven efficiency (Industry 4.0) to human machine collaboration that prioritizes resilience, adaptability, and ecological responsibility. Along side this, modern construction management technologies such as drones, virtual reality, and BIM enabled collaboration platforms are redefining project delivery, ensuring better resource allocation and improved environmental performance. The collective insights from these research efforts illustrate a shared trajectory: the fusion of technological innovation with ecological stewardship. Whether through AI optimized material design, IoT enabled monitoring, seismic risk automation, fuzzy decision making, or Industry 5.0 practices, the future of civil engineering is being reshaped into one that is intelligent, responsive, and sustainable. By adopting these approaches, the construction sector can address its dual responsibility: enabling infrastructure growth while minimizing environmental impact. Together, these technologies provide a framework for building infrastructure that not only withstands the challenges of climate change and rapid urbanization but also contributes positively to global decarbonisation efforts. The transformation of civil engineering is not simply a matter of technological evolution it is a necessary step toward ensuring resilient, smart, and environmentally responsible infrastructure for future generations.

Civil engineering is undergoing a transformative shift driven by artificial intelligence (AI), the Internet of Things (IoT), automation, and sustainable practices. Across multiple studies, AI has demonstrated its potential to optimize material design, enhance monitoring systems, and support resilient infrastructure (Lavercombe et al., 2021 [1]; Manzoor et al., 2021 [6]). Machine learning models have been effectively used to predict the compressive strength and embodied carbon of eco-friendly concrete (Lavercombe et al., 2021 [1]; Ramesh et al., 2025 [4]), while AI-based life cycle analysis offers improved approaches for evaluating the sustainability of geopolymer concrete (Ramesh et al., 2025 [4]).

In parallel, research supports the use of quarry dust and industrial by-products as environmentally responsible alternatives to natural aggregates, enabling low-carbon construction (Braimah et al., 2024 [5]; Kaja and Goyal, 2023 [12]). In the field of structural health monitoring, the integration of Edge AI allows for real-time crack detection in bridges, improving public safety and reducing data latency (Mishra et al., 2023 [2]). Furthermore, Generative AI combined with Building Information Modeling (BIM) facilitates the development of automated structural design pipelines, enabling regulation-compliant and diverse design outputs (y, transportation, and urban utilities (Oladele, 2024 [9]). Meanwhile, platforms such as RAPID-SIS are streamlining disaster response by automating the analysis of seismic accelerograph data (Iglesias & Pinzón, 2025 [10]). In transportation, fuzzy logic is increasingly applied to manage uncertainty, optimize traffic flows, improve safety, and assist autonomous vehicle operations (Dobrodolac et al., 2025 [11]).

At the industrial level, the adoption of Industry 5.0 technologies like AI-powered virtual assistants in concrete production facilities has shown to enhance process efficiency, reduce human error, and support sustainable manufacturing practices (Torregrosa Bonet et al., 2025 [7]).Together, these technological advancements underscore the convergence of digital innovation and environmental responsibility, laying a solid foundation for the development of resilient, sustainable, and smart infrastructure (Manzoor et al., 20291 [6]; Verma, 2023 [8]; Guo & Guo, 2025 [13]).

II. IMPLEMENTATION

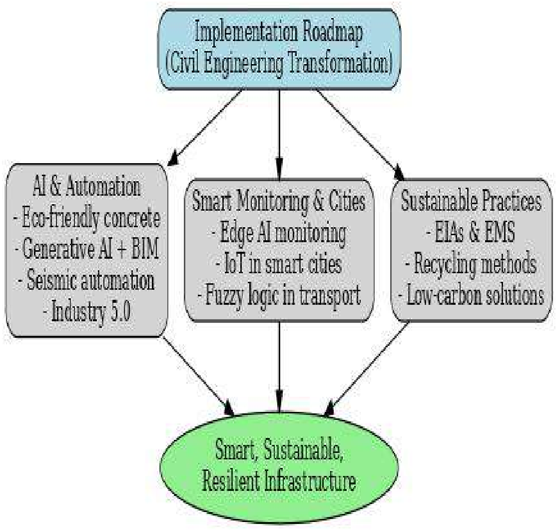

Fig. 1: Schematic Representation of transformation in Civil Engineering

The flowchart represents a practical roadmap for implementing the innovations discussed across the eight research papers. It begins with the overarching goal of Civil Engineering Transformation and then illustrates how different technological and sustainable approaches converge to achieve smart, sustainable, and resilient infrastructure. The first stage focuses on AI for eco friendly concrete, where machine learning models are applied to optimize mix designs using supplementary cementitious materials (SCMs) and geopolymer binders. By predicting strength, durability, and embodied carbon, these models reduce dependence on cement and directly contribute to decarbonisation. This is complemented by life cycle assessment (LCA) tools that evaluate the environmental, social, and economic impacts of materials. Parallel to material innovation is the use of Edge AI for structural health monitoring. This involves equipping bridges and critical structures with sensors and cameras connected to local processors. Instead of sending massive datasets to remote servers, edge devices analyze data on-site, providing real time crack detection and predictive maintenance alerts. Together, these approaches reduce failures and enhance structural resilience. The next stage highlights Generative AI integrated with BIM, which automates the design of structural models under defined constraints such as safety codes and sustainability goals. This accelerates design timelines and improves adaptability. Meanwhile, IoT applications extend digital intelligence across entire cities, enabling real-time optimization of transportation networks, energy grids, and utility systems. Seismic resilience is addressed through RAPID-SIS, an automated system that processes accelerograph data during earthquakes. By delivering corrected parameters and engineering ready outputs in minutes, it supports faster decision making for emergency managers. Similarly, fuzzy logic models strengthen transportation engineering by handling uncertainty in traffic flows, accident prediction, and logistics optimization. These adaptive tools improve safety and efficiency in increasingly complex mobility systems. At the organizational level, Industry 5.0 practices emphasize human machine collaboration. AI powered assistants in concrete plants, drones for construction monitoring, and VR-based project simulations support operators in achieving higher accuracy, safety, and sustainability. Alongside these, sustainable construction practices such as Environmental Impact Assessments (EIA), waste recycling, and green certifications ensure ecological responsibility.

Finally, all these innovations converge at the bottom of the flowchart into the shared outcome: Smart, Sustainable, and Resilient Infrastructure. This reflects the combined potential of AI-driven material design, IoT enabled monitoring, seismic automation, fuzzy logic, and Industry 5.0 practices. The flowchart demonstrates that while each innovation is powerful individually, their true impact emerges when implemented together as part of an integrated strategy for civil engineering.

2.1 Using AI for Greener Concrete:

Concrete will remain the backbone of construction for the foreseeable future, but its reliance on cement makes it one of the world's biggest carbon emitters. To cut this footprint, researchers propose using supplementary cementitious materials (SCMs) like fly ash, slag, or quarry dust. The challenge is predicting how these new mixes will perform. This is where machine learning (ML) becomes valuable. By training ML models on large sets of experimental data, engineers can predict strength, durability, and carbon emissions without endless trial and error in the lab. In practice, construction firms could build digital libraries of past test results and feed them into algorithms such as Random Forest or Gradient Boosting. These models could then be integrated into design software, allowing engineers to quickly find the best low-carbon mix for a given project. For geopolymer concretes, AI can be linked with life cycle assessment (LCA) tools to give a full picture of environmental impact, including energy use and waste. This means sustainability is considered right from the start of the design process rather than as an afterthought.

2.2 Smarter Monitoring with Edge-AI:

Traditional inspections of bridges and large structures often involve manual checks, which can be slow and sometimes miss hidden issues. By installing sensors and cameras linked to edge-AI systems, structures can monitor themselves in real time. These devices analyze data locally right at the site so cracks or unusual stresses are detected immediately. Alerts can be sent to engineers' phones, allowing them to respond quickly before a small defect becomes a safety hazard. A practical way to start is with pilot projects on older or high risk bridges. Once proven reliable, this approach could be scaled up across transportation networks. The benefits are clear: less downtime, safer structures, and reduced maintenance costs.

2.3 Generative AI in Design:

Designing safe and efficient structures has always required balancing codes, costs, and creativity. Generative AI, when combined with Building Information Modeling (BIM), brings automation into this process. Engineers provide the design constraints such as loads, dimensions, and sustainability goals and the AI generates multiple viable options. This doesn't replace human judgment but speeds up the early stages of design while ensuring compliance with standards. To implement this in practice, firms would need to update their BIM platforms with generative design plugins and train staff in how to interpret and refine AI-generated options. Over time, regulatory bodies could provide guidelines for approving AI-assisted designs, making the technology more widely accepted.

2.4 IoT for Smart Cities:

The Internet of Things (IoT) has the power to connect entire cities through networks of sensors. In civil engineering, this translates into adaptive traffic lights that reduce congestion, smart grids that balance electricity demand, and water systems that detect leaks in real time. For implementation, city governments need interoperable platforms where data from transport, energy, and utilities can be shared and analyzed together. This also means investing in reliable communication infrastructure such as 5G and edge computing, as well as enforcing cybersecurity and privacy protections. Without these, IoT systems could face technical breakdowns or even security threats. But with the right safeguards, IoT can make urban areas more efficient, sustainable, and livable.

2.5 Seismic Safety with RAPID-SIS:

Earthquake-prone regions face unique risks that require fast responses. The RAPID-SIS system automates the processing of seismic data, turning raw accelerograph readings into usable engineering reports within minutes. Implementing this means setting up dense networks of seismic sensors connected to national or regional monitoring centers. When an earthquake occurs, the system automatically generates corrected acceleration and response spectra, which can be sent directly to emergency managers and engineers. For long-term success, training programs would be needed so civil protection authorities know how to interpret these outputs. Integration with early warning systems could further strengthen disaster preparedness.

2.6 Fuzzy Logic in Transportation:

Traffic systems are complex and full of uncertainty drivers react differently, weather changes conditions, and accidents can disrupt flow. Fuzzy logic is well suited to such environments because it mimics human reasoning in uncertain situations. In practice, this could be applied to adaptive traffic signal systems, accident prediction software, or even autonomous vehicle navigation. For logistics, fuzzy models can optimize routes and warehouse placement, reducing costs and improving service efficiency. Implementing this requires partnerships between transportation agencies, software developers, and researchers, ensuring the models are tailored to local conditions.

2.7 Sustainable Construction and Industry 5.0:

The construction industry has long faced criticism for its environmental impact. Implementing sustainable practices means making Environmental Impact Assessments (EIA) and Environmental Management Systems (EMS) mandatory and actually enforcing them. Companies can use recycled aggregates, energy efficient equipment, and green certifications such as LEED or BREEAM to prove their commitment. At the same time, Industry 5.0 is shifting focus from pure automation to collaboration between humans and intelligent systems. In concrete plants, AI powered assistants could help workers mix materials more accurately, reduce waste, and detect errors before they become costly. On construction sites, drones can monitor progress, while virtual reality tools can bring stakeholders together for immersive project planning. The goal is not to replace humans but to empower them with smarter tools that make work safer, faster, and more sustainable.

2.8 Roadmap for Integration:

For these innovations to move from research into practice, a clear roadmap is needed:

1. Start Small: Pilot projects on eco-friendly mixes, smart bridges, or IoT based traffic systems help prove the benefits before scaling up.
2. Build Skills: Engineers, managers, and workers need training in AI tools, digital workflows, and sustainability standards.
3. Supportive Policies: Governments should encourage adoption through incentives, updated codes, and stricter sustainability targets.
4. Shared Data Platforms: Open and standardized data exchange ensures AI models, IoT devices, and BIM platforms can work together.
5. Adapt to Context: Local conditions climate, materials, regulations must shape how each technology is applied.

III. SUMMARY

The reviewed research highlights how civil engineering is rapidly evolving through the adoption of digital tools, sustainable practices, and intelligent systems. At the material level, machine learning is being used to optimize eco-friendly concrete mixes by predicting strength, durability, and embodied carbon. This allows the use of industrial by-products such as fly ash, slag, and quarry dust, while AI based life cycle analysis ensures that geopolymer concretes are evaluated across environmental, social, and economic dimensions. For infrastructure monitoring and design, edge AI frameworks provide real-time crack detection in bridges, reducing the risks of failure, while generative AI integrated with BIM accelerates the creation of diverse, regulation compliant designs. IoT systems extend this intelligence across cities by enabling adaptive traffic control, energy efficiency, and utility management. At the same time, seismic automation platforms like RAPID-SIS transform disaster preparedness by delivering instant, accurate engineering reports during earthquakes. Transportation networks benefit from fuzzy logic models, which improve traffic forecasting, accident prediction, and autonomous vehicle decision-making in uncertain environments. At the industrial scale, Industry 5.0 introduces human machine collaboration, where AI assistants, drones, and VR technologies support operators to improve accuracy, efficiency, and sustainability in construction projects.

Together, these innovations show that the future of civil engineering lies at the intersection of digital transformation and ecological responsibility. By embracing AI, IoT, seismic automation, fuzzy logic, and Industry 5.0 practices, the sector can build infrastructure that is not only stronger and safer but also sustainable and resilient for generations to come.

IV. CONCLUSION

The findings consistently emphasize that the sector can no longer rely on traditional methods if it is to meet the challenges of climate change, rapid urbanization, and growing infrastructure demands. Instead, a combination of artificial intelligence (AI), Internet of Things (IoT), seismic automation, fuzzy logic, and Industry 5.0 practices is required to reshape how infrastructure is designed, built, and maintained. At the materials level, machine learning models have proven capable of optimizing ecofriendly concrete design by predicting both strength and embodied carbon. This makes the large scale use of supplementary cementitious materials and geopolymer concretes more practical, directly contributing to decarbonisation goals. In parallel, AI-based life cycle analysis ensures that sustainability assessments are comprehensive, spanning environmental, economic, and social impacts. For infrastructure monitoring and design, edge AI frameworks and generative AI integrated with BIM provide powerful tools for improving safety and accelerating design workflows. These technologies minimize human error, reduce costs, and expand the creative possibilities available to engineers. Similarly, IoT systems enhance the efficiency of smart cities, while seismic platforms such as RAPID-SIS strengthen disaster resilience by automating earthquake data processing. Fuzzy logic brings adaptability to transportation networks, supporting better traffic management, accident prediction, and autonomous vehicle operations. At the organizational level, Industry 5.0 introduces a human machine collaboration model where AI systems support, rather than replace, human expertise. Virtual assistants in concrete plants, drones for site monitoring, and immersive project simulations through VR demonstrate how technology can increase efficiency while still centering human decision making. Together, these advances support not only technical progress but also ecological responsibility and long term sustainability. By doing so, the industry can move from being a contributor to environmental problems to becoming a central force in solving them. The collective evidence from these studies makes it clear: the digital and sustainable transformation of civil engineering is not just possible, it is essential for building the resilient cities of tomorrow.

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International Journal of Advanced Engineering Research and Science (IJAERS)
Peer-Reviewed Journal
ISSN: 2349-6495(P) | 2456-1908(O)
Vol-12, Issue-10; Oct, 2025
Journal Home Page Available: https://ijaers.com/
Article DOI: https://dx.doi.org/10.22161/ijaers.1210.6

Integrating Water Resource Management into Sustainable Built Environments

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Received: 25 Sep 2025,

Received in revised form: 19 Oct 2025,

Accepted: 21 Oct 2025,

Available online: 25 Oct 2025

***Keywords*— Concrete-filled steel tubular columns (CFST) column, Durability, Predictive modelling, Zero Energy Buildings (ZEBs)**

***Abstract*— New approaches in civil and environmental engineering will be needed in the future of struggle of climate change, urbanization, and resource scarce situations. This analysis of the studies encompasses a critical aspect of sustainable infrastructure and new construction materials, management of water, and stability of structures. The principles of the earthquake-resistant design are devoted to the unified geotechnical innovations and structural innovations to add to the seismic risk reduction and buildings safety. Besides this, ANN models are highly predictive on optimistic cross-sectional aspects of concrete filled steel tubular (CFST) columns, which can offer a structural designer with a solid design computing instrument. In the context of water management, use of treated wastewater in artificial recharge of water offers research that will prove that groundwater tables of arid and dry regions such as Iraq can be significantly boosted to Suit a greater agricultural production and battle desertification. The corresponding search of the Zero Energy Buildings (ZEBs) refers to the extreme need to reduce the emissions of carbon by relying on the passive structure, energy efficiency, and integration of renewable sources, and the study of self-healing construction materials implies the efficient solutions to extend the period of lives, reduce the number of repairs, and extend the term of existence of infrastructure. Long-term perspectives of the world water sources imply that act of reciprocity create a relationship between the approaches of farm demands, shortage of freshwater and biodiversity elimination and it is famed that conservation, reuse and increase in effectiveness are very vital.*

I. INTRODUCTION

Infrastructure as a concept has been radically conceptualized in terms of the inception conceptualization, design and building concept in the 21 st century. Unlike the old-fashioned model of engineering where much attention was often directed at functionality and the short-term parsimony, the new generation of engineering has to rest upon the principles of multi dimensionalism of goals that include sustainability, resiliency, safety, and adaptability. Such decisions are by the combined forces of devastation of the environment, increasing capacity of disaster potentials and the urgent need to reduce the emission of greenhouse gases. This, in turn, resorts to a greater power of interconnection between spheres of the structural engineering and material science, water resource control and the environmental policy. Kumar, R. & Tanaka (2022) [1], The occurrence of earthquakes is known to be one of the most significant challenges to built-in environments since it is one of the natural hazards. The terrible aftermaths of the earthquake action in the overcrowded regions have standardized the need of the earthquake resistant design. Besides the structural codes, the methodology has a consciousness of the social conditions of the soil, characteristics of material and innovative forms of construction that reduce vulnerability and save lives. Because of finding areas in the future along with aggrandizement of urban systems, particularly the ones within seismicity, the topicality of the earthquake resistance strategies never was as high as it is presently. Singhand Li (2023) [2], New frontiers in the computational intelligence in civil engineering have opened the way to new opportunities just like it did to structural safety. The artificial neural networks (ANNs) are one of those improvements that give the opportunity to compute and optimize such complex structural parameters with a high preciseness. One instance of how the data-driven approach can be applied to supplement the existing research including experimental and analytical, involves concrete-filled steel tube column (CFST) studies, offering faster, more flexible and cost-effective research implementations. Such are also the tools that give rise to the automation process in designing, which involves experimenting with different designs and trial-and-error experiment, increasing the precision of the construction planning. And yet another vital building block of the modern infrastructure planning is a sustainable management of the water resources (Al-Mutairi, S. and Hussain, M. 2024) [3]. Climate change coupled with population growth has resulted in a heightened water scarcity in the world. A case in point is that of the case of the Al-Dibdibba aquifer in Iraq whereby artificial recharge with treated wastewater, which has been applied through injection wells can restore sinking groundwater table as well as greater agricultural output. It is not only an adequate solution to the stifling economies but also puts pressure on recycling wastewater during sustainable growths. By engaging the modern hydrological modelling, the scenario testing, the water resource engineers will be able to ensure sustainability of the water aquifer in the long run and at the same time cover agriculture, industry and domestic demand. Petrov and Smirnova (2022) [4], again, it is important to reduce the amount of carbon that is produced by the building industry alongside with reducing the usage of available resources. Major contributors to the climate change are the clients of housing and public buildings as approximately 30-40% of all the energy consumed in the world is attributed to housing and public buildings. Some of the concepts that have emerged to become ground breaking are Zero Energy Buildings (ZEBs) which deals with high energy demand, ultra-low energy, high efficiency insulation, passive heating and cooling and incorporation of renewable energy. It might be a a bit higher than the price of building early and the benefits of ZEBs in terms of lifecycle, along with the amount of energy that saves and will reduce emissions will make them incomparable in terms of environmental and economic performance. Garciaand Nakamura (2023) [5], Technology: Self-healing technologies are shaking the material level Construction science. Technology Self-healing materials are based on the natural biology and aim at repairing the micro-cracks and local damage themselves, the materials are designed to increase working life of the structures as well as reduce maintenance cost. Such application of the technologies will mirror the broader sustainability aims such as in the minimization of waste products as well as reduction of carbon-intensive repairs and the expansion of the structure of vital infrastructure such as bridges, tunnels and high-rise buildings. Johnson and Adewale (2024) [6], The depletion of biodiversity and increase in agricultural activity are further examples of the interconnection between engineering and environmental system through third world perceptions of water resources. Water availability is directly connected to food security because close to 70 percent on all fresh water on Earth is drank up in agriculture. The unreasonable exploitation, pollution, and the slave rule do not merely jeopardize the harvests but contribute to the increase in the number of the species extinction in both the aquatic and land ecosystems. Hence water efficiency, recycling and conservation is not an option but a need to redefine the human consumption against environmental salvaging to balance the interest of both sides. Alabi (2022) [7], The concept of sustainable and climate-resilient infrastructure can be used to bring together all these strands to the system. One example is to include green building elements, renewable energy technologies, advanced nature-sourced solutions, and technology-driven smart digital infrastructural design to allow the engineers to lower the level of adaptive characteristics to create infrastructure that would be capable of withstanding the intensity of the weather but still not alter the environment in an adverse manner. Informed planning, which has been co-ordinated by climate models and joint policy framework, stipulates that infrastructure fulfils not only the sustainability requirements, but also responds to any future uncertainty. The future of civil engineering, in simple terms, is systems thinking approach in the form of a combination of innovativeness and accountability. By means of the benefits realized through the aid of calculations, top-tier materials, water-conserving technologies and eco-friendly building, the engineers will be able to create the infrastructure which is robust, efficient, and corresponds to the concept of a sustainable evolution. An accumulated amount of such efforts can be seen as the cornerstone to a mature environment that can possibly survive in the environment of growing environmental and social demands. Mahadeva, M., and Sriram, A. V. (2024) [8], reference evapotranspiration (ET_0), which is a key factor in estimating how much water crops need and understanding how climate change affects agriculture. Using the widely accepted FAO-56 Penman–Monteith model, the authors analyze how sensitive ET_0 is to various climatic variables like sunshine duration, wind speed, and relative humidity. They find that sunshine hours are most important in humid regions, while wind speed plays a bigger role in arid areas. The study also applies statistical tests (Mann–Kendall and Sen's slope) to detect trends in these variables over time. These insights are valuable for improving water management strategies in agriculture. 1–6. ISBN: 978-93-91535-62-9.

II. APPLICATIONS

1. Earthquake-Resistant Design Safere in Seismic Hospitals, Schools and Emergency Facilities. Still-operable high-rise buildings and bridges with isolated bases. Urban development organization in seismic territories.
2. Symbiosis of Structural Design Artificial Intelligence (ANNs). AUTO CFST column, beam and slab optimization design. Minimizes the expenses in construction and mistakes in design. Applied to the intelligent design systems to decide swiftly.
3. Restoration of dry aquifers (e.g. the Al-Dibdibba aquifer of Iraq). Increase in agricultural production by increasing ground water storage. Urban water control→ wastewater reuse.
4. Zero Energy Buildings (ZEBs) Offices, energy-neutral buildings and houses. Extinguishes carbon footprint of the construction industry (30 40 percent energy consumption in the world). Reduced cost in the long run even when the construction cost has increased.
5. The Self-healing Construction Materials. Prolongs existence of bridges, tunnels, pavements, dams. Minimizes maintenance expenses and unavailability. Helps in the creation of a circular economy with less waste and repair.
6. Water Resource Efficiency Agricultural drip and sprinkler irrigation. Reuse of greywater in metropolitan and industrial areas. Helps ensure biodiversity and at the same time provide human water.
7. Smart Investment and Resilience to Climate. Urban system- Flood-resistent urban drainage systems with real-time data monitoring. Green rooftops and cooling and stormwater wetland. Predictive maintenance IoT & AI-based sensors.

III. RESEARCH GAP

Artificial Neural Networks (ANN) have been a potent solution used in civil engineering in the recent years to positively influence the design of complicated structural subjects like concrete-filled steel tubular (CFST) columns. Such models have great benefits to predictive capabilities and computational ones especially when it comes to cross-sectional area and load carrying issues. Nevertheless, the existing theoretical advantages of ANN within structural engineering are well-described, but the use of ANN is mostly limited to controlled areas or those rich in data. There is an articulate weakness in implementing such models in the real-life, high-risk area- particularly in regions where there are seismic risks exposure and minimal resources to trustworthy other support building data like in Iraq and other desolate locations. Besides, ANN application on structural design is seldom combined with the presence of sustainability-based objectives such as low-carbon architecture, material waste, and sustainability during prolonged use. This piecemeal method fails to provide a company with another critical chance to employ smart modelling, not only to enhance performance, but also to improve infrastructure resiliency and sustainability in the susceptible societies. Interdisciplinary studies performing a unification of ANN-based modeling, seismic resilience, and sustainable construction practices are needed to bridge this gap. This kind of integration would enable more situation-specific, adaptive and futuristic design models that are responsive to the compounding stresses of climate change, resource scarcity and urbanization.

IV. RESULTS AND DISCUSSION

An understanding of how to achieve sustainable, resilient, and technologically advanced practices in the sphere of civil engineering will involve the implementation of a multi-layered framework spanning the gap between the research findings and actual practices. Based on the mentioned research, the implementation process includes structural resilience, computational intelligence, water resource sustainability, energy efficient buildings, material innovation and climate resiliency infrastructures. All fields have their specific contribution to the emergence of burning issues in the world like natural disasters, climate change, water shortage, and urban sprawl. Blocks KimonoPaulsa Structural Safety with Earthquake Resistance. Disaster resilience in infrastructure basing is carried out by earthquake-resistant design. Implementation issues include the following: Seismic Assessment and Zoning: Accomplishment of site-specific hazards mapping relying on the seismic history, interaction of soil and structure, as well as micro-zonation. Design Strategies: Using ductile detailing, shear walls, bracing systems and base isolation devices that will permit controlled deformation to prevent collapse. The choices of materials used: The use of high-strength, low-weight composites and materials that dissipate energy, in order to minimize the rate of inertial loads. Simulation and Modelling: Predicting the performance of the buildings under various strengths of seismic activities through the ETABS tool, SAP2000 tool, and tool ANSYS. Capacity - Building: Education of engineers, architects and contractors on countrywide earthquake-res able design procedures to guarantee the practice goes beyond the theoretical phase. A case in point is the implementation of base-isolated foundation in hospitals and schools to make sure that the execution proceeds even upon the occurrence of high-magnitude earthquake. To do Structural Optimization Artificial Intelligence. ANNs offer an effective way of forecasting and optimizing the design of the structural members, especially, Concrete-Filled Steel Tubular (CFST) columns. Theory can be applied in practice and can involve Data Integration: Gathering vast amounts of data about lab tests, field research, and synthetic modelling, which evaluates in ANN frameworks. Model Deployment: Activation of trained ANN models into structural design software to provide ideal recommendations on cross-sectional dimensions. Decision Support Systems: To ascertain reliability, engineers are permitted to conduct a comparison between ANN forecast and the conventional code-based design. Scalability: ANN models can be used in other structural components like beams, slabs, and foundations so as to have one platform where smart design was done. This reorientation towards the use of AI functions of design saves time, costs and human error, and increases the accuracy in a changing load condition. Man-made Groundwater Recharge and Latent Groundwater Sustainability. In arid areas, shortage of water would require new forms of recharge techniques. The steps involved in its implementation are Utilization of Treated Wastewater: Practices Multiplying aquifer recharge with tertiary treated effluent in municipal wastewater treatment devices. Well-Based Recharge Systems: Location of injection wells depends on the effective location of wells to achieve maximum percolation and less evaporation. Hydrological Modelling: The use of MODFLOW to simulate the effect of recharge in GMS (Groundwater Modelling System) to emulate various situations. Monitor and Control: implementation of sensor and piezometers to monitor the changes in the ground water levels and effectiveness of recharge. Agricultural Integration: Growing irrigated areas by increasing storage of aquifers thus enhancing food security. Artificial recharge, as in the Iraqi Al-Dibdibba aquifer project, increased the levels of water up to 3 meters, recovering the agricultural productivity of over 90 plus km 2 of land. Applications for Zero Energy Buildings (ZEBs). Constructed structures and buildings are important in the use of energy and also as contributors to CO 2. ZEB principles need to be conducted in a holistic design approach: Building Envelope: This is done by laying a high-performance insulation, airtight designs, and energy efficient windows to reduce the heat transfer. Passive Systems: Passively includes solar orientation, shading systems, natural ventilation and daylighting to lower the artificial energy consumption. Active Systems: Photovoltaic panels, wind turbines and solar thermal collectors are added to the system to supply the energy requirements. Smart Energy Management- This involves the selling of excess energy through the use of automated systems to optimize demand and supply, as well as the use of stored energy when necessary. Economic Feasibility: Independence by subsidizing and introducing a tax benefit and proving it by demonstrations. The case studies of Europe and Russia show that ZEBs with an increased initial cost can payback in 10-20 years due to lower energy usage in the operations. Use of Self-healing Construction Materials. Self-healing materials are a sustainable infrastructure development. They need the following to be implemented: Microcapsule Technology: Incorporation of capsules made in concrete which release along cracks and contain therapeutic properties inside them. Bacteria-Based Competent: The uniform introduction of calcite-precipitating bacteria that form when exposure to moisture in order to close cracks. Intrinsic Healing Mechanisms: Restoring mechanical properties by using reversible polymeric bonds that self-repair. Pilot Testing: Concrete standard testing in bridges, tunnels, and pavements is to be applied self-healing to make concrete large-scale viable. Lifecycle Cost Analysis: Showing how it saves money by lowering the rate of repairs, increasing service life and the time spent iniguiring. Self-healing materials are included in the spirit of circular economy, as creating them will decrease the wastage and rely on energy-consuming solutions aimed at restoring their functionality. Water and Agricultural Productivity. Optimal utilization of water resources is essential to food security on the planet. The pathways of implementation are: Modern Irrigation Systems: A change to drip and sprinkler irrigation will cut by 40 its leakage of water. Recycling and Reuse: It promotes the utilization of grey water and treated wastewater to irrigate fields and industries otherwise. Policy and Governance: To create the benchmarks of water-use efficiency and digitalize pricing policy, impacting over-extraction. Ecosystem Integration:

Optimizing the use of agricultural waters with the conservation of biodiversity through the maintenance at minimum ecological streamflow of rivers. These strategies guarantee the fact that the process of agriculture requiring approximately 70-percent of all world freshwater turns out to be more sustainable and less damaging to nature. Skilled Climate-Flexible and Clever Infrastructure. The resilience implementation in the infrastructure involves integration of green technologies, intelligent systems, and flexible planning: Green Materials: gPASS Additional - Concrete, Consistencies, and Composites Properties Concrete Reuse and Recycling The best methods to decrease the lifecycle emissions of concrete involve recycling of aggregates, implementing high-performance concretes and use of low carbon cements. Solutions that are easy to implement natural solutions- wetlands, mangroves, bioswales, green roofs can be implemented to reduce flooding and urban heat islands. Smart Infrastructure: Implementation of IoT-based sensors, intelligent predictive maintenance procedures, and smart grids in real-time adjustment. Risk -based Planning: integrated mitigation: integration of climate projections into infrastructure design codes, to consider sea-level rise, heat waves, and extreme rainfall. Collaborative Models: Spurring public-private publics (PPP) and contribution to scale adoption of sustainable infrastructure. As an illustration, intelligent floodproof urban water drainage networks are currently being tested in nation cities of Europe, whereby real-time interacting alters water flows during downpours.

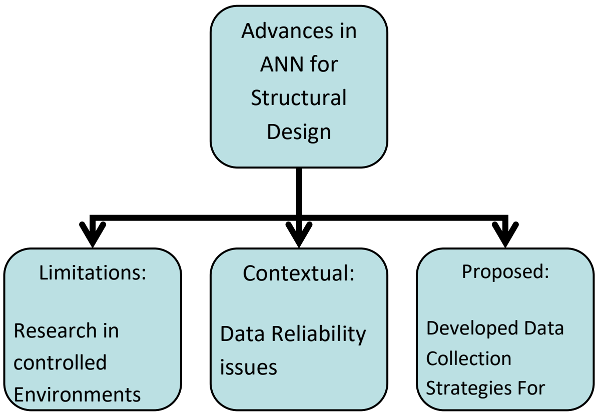

Fig.1: ANN in Structural Design with CFST Modelling

This flowchart shows how Artificial Neural Networks (ANN) are being applied to structural design, with a focus on Concrete-Filled Steel Tube (CFST) column modelling. While ANN has advanced a lot, current research is mostly done in controlled settings with data only from reliable regions. These studies rarely address seismic risks, sustainability, or the difficulties faced in developing countries. Real-world challenges add another layer—unreliable data, variations in construction practices, different levels of seismic risk, limited material availability, and financial barriers. All these issues reveal the need for a new kind of design framework: one that is ANN-supported, sustainable, and resilient to earthquakes. The proposed way forward involves creating better data collection methods for low-resource regions, adding seismic risk considerations to ANN models, incorporating local practices, using eco-friendly materials, factoring in social and economic realities, and testing these frameworks with real-world case studies. This holistic approach can make ANN-based CFST design more practical, resilient, and sustainable worldwide.

V. SUMMARY AND CONCLUSION

The multi-dimensional approach based on the synthesis of research studies contributes to the further evolution of civil engineering activity in terms of climate change, the lack of resources, and vulnerability to a disaster to meet the needs of the modern world in the situations of climate change, resources scarcity, and disaster predisposition. The two publications provide their independence in terms of knowledge on how to develop strong, sustainable, and intelligent infrastructure systems. The research of the earthquake resistant design attracts attention to the necessity to unite opinion of the geology application with the structural mechanics and the innovative approaches to constructions to minimize the harm of the seismic events. This will ensure good infrastructure in the prone regions are able to sustain the disasters to protect human lives and property. The article about artificial neural networks (ANNs) demonstrates how calculation intelligence may be used to change the structural design in particular with concrete on steel tubular columns (CFST). ANNs are capable of anticipating maximum accuracy cross-sectional dimensions since they are trained with considerable volumes of data, and hence they can be easily designed as models, hence reducing the use of costly experiments and maximizing the accuracy of it. The solutions to the arid and semi-arid regions where lack of water is experienced are provided by artificial recharging of the ground waters. All these may be accomplished by injecting treated wastewater in certain wells which will enhance the normal level of the aquifer, this will serve in restoring agriculture and warding off desertification. The findings substantiate the significance of the numerical modelling application and sustainable reuse of water [the management] of the long-term resource management. Zero Energy Building (ZEB) concept contributes to the impulsive need to curb the use of energy and carbon emission by the building industry that takes up 30-40 percent of the total world energy consumption. The three ways to accomplish generic ZEBs are the passive, renewable energy solutions, and intelligent energy control of houses and buildings that offer cost-efficient and sustainable housing planning and building solutions to the urban housing project and institutional buildings. At the same time, the self-rep downloading materials are the fresh concept of environmental friendliness. According to the natural biological processes, the materials automatically reconstitute the micro-cracks and rebuild the stability. They reduce costs of maintenance and extend service life and help change the approach in the use of a circular economy in building. The issues of water resource scarcity in the world are brought into the limelight through the water resources study that reveals that biodiversity and agriculture are closely related to fresh water. Agriculture uses up more than 70 percent of freshwater resources, which adds food security risks and ecological pressures. Throughout all the studies carrying out the reviewed research we noted that the future of civil as well as environmental engineering will be to develop the system that will be handed over in the future in the chronicle of the infrastructure which will be sustainable, bound up and receptive in nature. All research papers relate to a considerable aspect of this vision. The designs are earth shaped to ensure that the structures are safe in the earthquake prone areas thereby saving lives and minimizing losses. Artificial neural network (ANN) application in two studies involving the design of concrete-filled steel tubular (CFST) columns, transformational opportunities of computational intelligence are seen with regard to optimization of structural performance. Projects with artificial recharge show that, under the influence of expanded LAW, one can recycle wet aquifer that can be utilized in water security and agricultural productivity in arid regions. The other concept that demonstrates the necessity of the need to make the carbon emissions reduction in building the sphere urgent is the idea of the Zero Energy Buildings (ZEBs) when the practice of passive construction and the application of renewable energy and advanced building management systems is under discussion. Technological solutions that can result in these strategies cannot be applied without the collaboration of governance and augmenting policies involving the community to scale them over a long time and succeed. In conclusion, structural resilience, artificial intelligence, water sustainability, energy efficiency, material innovation and climate adaptation are basically components of a roadmap in future built environment. When these two research findings are integrated to practice, the way the engineers and the policymakers define the infrastructural systems becomes that which is protection-conscious to communities and economical in terms of resource bases and expediency in a real-life passage to the new environment of the 21 st century.

ACKNOWLEDGEMENTS

Firstly, the authors want to say 'thank you' to all the people and institutions who gave their time and energy for the development of this paper. We would particularly love to thank the academic mentors and the research supervisors. They have played a very important role through the whole research process by their precious guidance and constructive feedback. We are also glad to extend our thanks to the institutions and the organizations that have given us the data, the necessary materials, and the technical support, which has enabled us to delve into sustainable infrastructure, advanced construction materials, water management, and structural resilience.

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International Journal of Advanced Engineering Research and Science (IJAERS)
Peer-Reviewed Journal
ISSN: 2349-6495(P) | 2456-1908(O)
Vol-12, Issue-10; Oct, 2025
Journal Home Page Available: https://ijaers.com/
Article DOI: https://dx.doi.org/10.22161/ijaers.1210.7

Dynamic Vibration Protection of a Mechanical System with a Finite Number of Degrees of Freedom

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Received: 16 Sep 2025,
Received in revised form: 14 Oct 2025,
Accepted: 19 Oct 2025,
Available online: 23 Oct 2025

***Keywords*— vibration, active vibration isolation coefficient, electrodynamic vibrator, Gurwitz stability criterion.**

Abstract*—*In the conditions of constantly tightening requirements for vibration and noise, shown to modern power plants, the possibilities of passive vibration isolation are provided practically exhausted. As a result, in this situation, active vibration protection systems acquire decisive importance. In the work, the dynamics of two mass active vibration protection systems is developed. Its efficiency and stability areas are solved.

The most effective way to combat vibration is to reduce the variable forces in the sources and energy transmission chains (internal combustion engines, gear transmissions, electric motors, etc.). But, naturally, when designing sources, the key task is to fulfill the main functional task - to ensure the transfer of energy from the source to the receiver with maximum efficiency while necessarily meeting the requirements for strength and resource characteristics. Vibration activity often recedes into the background. Hence the limitations of this way of combating vibration.

To protect technical and biological objects from vibration excitation in the low-frequency range, a huge number of vibration protection systems have been developed, based on the use of a wide range of shock absorbers. Such vibration protection systems are called passive. However, their use in many cases turns out to be ineffective, for example, when protecting objects from vibration spectra changing over time.

Recently, automated vibration protection systems have found application, which are called active vibration protection systems. [1,2]. The creation of effective active systems for vibration damping of low-frequency vibration of various mechanisms, excited by the action of variable forces, has been the goal of the work of many researchers over the past several decades. In general, control of such systems can be implemented on the principle of disturbance compensation, compensation of deviation of the controlled variable, or a combination of both these methods.

Experience in creating active vibration damping systems has shown that the most promising in terms of complete reproduction of variable forces, comparative ease of implementation and control, and lack of sensitivity to negative environmental factors are electrodynamic vibration protection systems, in which an electrodynamic vibrator serves as an actuator [3]. A characteristic feature of active systems is the use of active circuits consisting of measuring, amplifying and executive elements. The latter generate a force that allows reducing the dynamic loads acting on the protected object.

In active vibration protection systems, information about the nature of disturbances, their frequency and amplitude composition is required to create a control action (control). The role of sources of this information is played by electrical vibration converters, which act here as converters of motion parameters (force, acceleration, displacement) into electrical signals (voltage, current). The converters used (displacement sensors, force sensors, accelerometers, etc.) must have a sufficiently wide frequency range (at least five times wider than the frequency range of the measured signal) and a low coefficient of nonlinear distortion. Electrical signals as control actions must be proportional to the disturbing force Q(t). When the frequency and amplitude of the external action change, the frequency and amplitude of the current (voltage) should change in a similar way. An oscillatory system with an electrodynamic vibrator can be considered as an object of automatic control and the methods developed in the theory of automatic control can be used to study it [3,4]. When compiling a system of equations describing the dynamics of a mechanical oscillatory system with an electrodynamic force generator, both mechanical motion and electrical processes in the conductor circuit (moving coil) should be taken into account. In electrodynamic devices, the current for creating force arises as a result of the movement of either the conductor itself or its suspension points.

For instance, let us consider a mechanical system consisting of one body. Let us consider the mechanical system shown in pic. 1, the scheme of active vibration protection systems, in which the vibrator body is considered vibration-isolated from the rest of the system. This allows us not to take into account the dynamic reaction force from the vibrator body when constructing a mathematical model. The force F generated by the vibrator acts on the base. Dissipative elements with rheological properties are included parallel to the elastic connections. A force sensor is installed between the "spacer" plate and the fixed base, converting the force acting on the plate into a control signal.

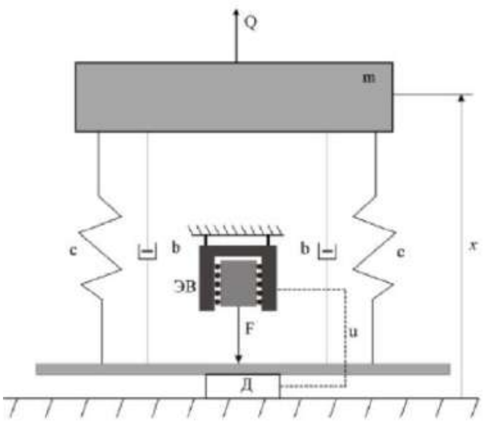

Fig. 1. Active vibration protection systems with one degree of freedom

Electrical signals as control actions must be proportional to the disturbing force Q(t). An oscillatory system with an electrodynamic vibrator can be considered as an object of automatic control and applied for its study developed in the theory of geometric servo-connections.

The behavior of this system will be described by equations

$$m\ddot{x} + c_p(x(t) - \int_{-\infty}^{e} R(t-\tau)x(\tau)d\tau = Q; \qquad (1)$$

$$L\frac{di}{dt} + Ri = U,$$

The first equation of system (1) characterizes the mechanical motion of the mass m, and the second - the electrodynamic equilibrium in the circuit of the vibrator's moving coil. In these equations, x is the absolute coordinate of the mass oscillations m.

$Q = Q(t)$ - external disturbing force, i - current in the control winding circuit of the electrodynamic vibrator, F - F(t) - ponderomotive force depending on the winding current (in particular, it occurs in geometric servo link), L, R-inductance and active resistance of the control winding, U- voltage on the winding of the moving coil, F(i) = B/i - Ampere force, co- instantaneous stiffness coefficient and $R(t-\tau)$ -relaxation core. Control is introduced as negative feedback on the total force acting on the base (sensor D):

$$U = -k_U(F(i) + cx(t) - \int_{-\infty}^{t} R(t-\tau),$$

where is the coefficient of proportionality between the voltage on the winding and the force $kU = k_\partial k_{yc} \succ 0$ ($k_\partial k_{yc}$ - sensitivity coefficients of the force sensor and amplifier gain). The paper [5,6] presents the results of calculations of active vibration protection of a mechanical system with one degree of freedom. We will conduct a study of models of active vibration protection systems with various connection schemes of an electrodynamic vibrator and application of an external dynamic load. In all cases, the task is to reduce the dynamic load on the foundation. Modeling is performed in the low-frequency range.

Let us consider a model of active vibration protection systems with two degrees of freedom. Let us assume that the task is to actively isolate some elastically fixed mass (ml) in the near-resonance range (relatively low frequencies are considered). An external disturbing force acts on the mass Q(t). In order to install the vibrator, additional mass is introduced. (m_2), fixed to the insulated mass by means of elastic elements (C_2). In parallel to the elastic connections, dissipative elements with a resistance coefficient are also included $b_{1,2}$. Between the "attachment" plate and the fixed base, a force sensor D is installed, converting the force acting on the plate into a control signal (voltage and at the coil terminals). The system is described by the equations:

$$m_1\ddot{x}_1 + c_1x_1 - c_2(x_2 - x_1) + b_1\dot{x}_1 = Q - F;$$
$$m_2\ddot{x}_1 + c_2x_1 - c_2(x_2 - x_1) + b_2\dot{x}_2 = F; \qquad (2)$$
$$L\frac{di}{dt} + Ri - U + Bl(x_2 - x_1) = 0.$$

The first two equations of system (2) characterize the motion of masses m_1 and m_2, the third - electrodynamic equilibrium in the circuit of the moving coil of the vibrator. In these equations x_1 and x_2 - absolute coordinates of the masses; Q = Q (t) - external disturbing force; i - current in the circuit of the control winding of the electrodynamic vibrator; F = F (i) - ponderomotive force depending on the current in the winding; L, R - inductance and active resistance of the control winding; U - voltage on the winding of the moving coil.

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International Journal of Advanced Engineering Research and Science (IJAERS)
Peer-Reviewed Journal
ISSN: 2349-6495(P) | 2456-1908(O)
Vol-12, Issue-10; Oct, 2025
Journal Home Page Available: https://ijaers.com/
Article DOI: https://dx.doi.org/10.22161/ijaers.1210.8

Evaluating the Preparedness and Resilience of Emergency Nurses in Disaster and Mass Casualty Situations from Private and Public Hospital

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Received: 21 Sep 2025,

Received in revised form: 22 Oct 2025,

Accepted: 25 Oct 2025,

Available online: 30 Oct 2025

***Keywords*— emergency nurses, disaster preparedness, mass casualty incidents, resilience, public hospital, private hospital, comparative study**

***Abstract*— Disasters and mass casualty incidents pose significant challenges to healthcare systems, requiring emergency nurses to respond with competence, efficiency, and resilience. This study aimed to evaluate and compare the preparedness and resilience of emergency nurses in public and private hospitals in the Philippines. Using a descriptive-comparative research design, a total of 30 emergency nurses (15 from public and 15 from private hospitals) were purposively selected as respondents. Data were collected through a structured survey questionnaire assessing demographic profiles and six key indicators: knowledge and training, emergency response skills, institutional support, psychological resilience, teamwork, and adaptability under pressure. Descriptive statistics (mean, standard deviation, frequency, and percentage) and independent samples t-tests were employed to analyze differences between public and private hospital nurses. Results showed that private hospital nurses generally scored higher across most indicators, with a statistically significant difference in knowledge and training ($p = 0.030$). Both groups exhibited high psychological resilience, teamwork, and adaptability under pressure, while institutional support emerged as an area needing improvement, particularly in public hospitals. The study highlights the importance of combining individual competency, structured training, and institutional support to enhance emergency nurses' preparedness and resilience, ultimately improving healthcare response and patient outcomes during disasters and mass casualty events.*

I. INTRODUCTION

Disasters and mass casualty incidents (MCIs) are unpredictable, high-impact events that place extraordinary demands on healthcare systems worldwide. These emergencies require rapid decision-making, effective triage, and coordinated multidisciplinary action, with nurses serving as vital frontline responders. Emergency nurses are responsible for providing life-saving interventions while maintaining patient safety in highly stressful and chaotic conditions. Their level of preparedness—encompassing knowledge, skills, and attitudes—directly influences the efficiency and quality of healthcare delivery during crises. Likewise, psychological resilience enables nurses to sustain performance, manage stress, and adapt effectively to unpredictable circumstances.

The increasing frequency and intensity of disasters globally highlight the need to strengthen preparedness among healthcare professionals. Previous research has revealed that while nurses understand disaster principles, many report insufficient preparedness in real-world emergencies [1]. Furthermore, psychological factors such as coping mechanisms, stress management, and adaptive capacity play a significant role in influencing nurses' competencies during high-pressure situations [2]. These findings suggest that preparedness is not only a technical construct but also a psychological one shaped by resilience and adaptive functioning.

Even in highly developed nations with structured emergency response systems, challenges persist in maintaining nurses' disaster readiness [3]. Continuous professional development and competency-based training are essential to bridge these gaps. In developing countries, however, preparedness issues are often compounded by limited infrastructure, unequal access to simulation programs, and inadequate institutional support [4].

In the Philippines, where typhoons, earthquakes, and volcanic eruptions frequently occur, the issue of nurse preparedness is particularly critical. Studies have shown that while Filipino nurses demonstrate awareness and commitment, their preparedness is constrained by limited disaster training, insufficient drills, and scarce medical resources [5]. Although nurses exhibit strong resilience and adaptability, systemic barriers such as lack of institutional support and limited continuing education hinder their ability to sustain effective disaster responses [6]. These findings imply that resilience, while valuable, cannot substitute for structured preparedness programs and strong institutional readiness.

Given these conditions, this study seeks to quantitatively evaluate the preparedness and resilience of emergency nurses in disaster and mass casualty situations. Examining the relationship between these two variables will provide empirical evidence to support the enhancement of nursing education, policy development, and institutional capacity-building.

1.1 Preparedness of Emergency Nurses in Disaster and Mass Casualty Situations

Preparedness among emergency nurses is a critical determinant of effective disaster response. It encompasses knowledge, technical skills, and situational awareness necessary for immediate decision-making during mass casualty incidents (MCIs). Recent studies reveal that although nurses recognize the importance of disaster readiness, their actual preparedness levels remain moderate to low [7]. Disaster-specific training, such as triage drills and emergency simulations, has been proven to enhance confidence and operational efficiency [8]. Moreover, the integration of interdisciplinary coordination models, where nurses collaborate closely with rescue teams and paramedics, strengthens overall system response and minimizes medical errors during high-casualty events [9].

Despite global efforts to advance preparedness frameworks, several challenges persist. Research highlights that gaps in knowledge, resource limitations, and inconsistent policy implementation hinder nurses' ability to respond effectively to sudden-onset disasters [10]. A study in Indonesia identified a strong correlation between nurses' disaster knowledge, participation in workshops, and their self-reported preparedness scores, reinforcing the importance of ongoing professional education [11]. Similarly, the incorporation of ethical guidelines and structured reporting protocols during crisis response enhances both patient outcomes and healthcare accountability [12]. Such findings indicate that preparedness must be sustained through continuous assessment and reinforcement rather than treated as a one-time competency.

In the Philippine context, nurse preparedness in disaster-prone regions remains a significant concern due to inadequate training programs and limited institutional support [13]. Studies show that Filipino nurses often rely on experiential learning during real-life emergencies, compensating for the lack of systematic disaster education. Additionally, the psychological toll of repeated exposure to traumatic events reduces performance efficiency and decision-making quality over time [14]. Hence, the development of standardized national disaster education and simulation-based competency frameworks is essential to ensure consistent and measurable preparedness among nursing professionals.

1.2 Psychological Resilience and Adaptive Capacity of Emergency Nurses

Psychological resilience plays a pivotal role in sustaining nurses' performance during disasters and MCIs. It enables healthcare workers to adapt effectively under pressure, manage emotional distress, and maintain cognitive function despite exposure to trauma. Studies have demonstrated that resilience is closely associated with self-efficacy, adaptive coping, and stress tolerance among nurses in emergency departments [15]. In high-intensity scenarios, such as burn disasters or public health emergencies, resilient nurses display greater emotional regulation and decision-making accuracy [16]. Simulation-based training programs that integrate psychological conditioning techniques have also been shown to improve adaptive capacity and reduce burnout rates [17].

Resilience is not solely an individual attribute but is influenced by organizational and social factors. Findings indicate that supportive leadership, peer relationships, and institutional culture contribute significantly to nurses' ability to recover from high-stress situations [18]. Conversely, environments with limited psychosocial support or poor communication channels exacerbate anxiety and emotional fatigue [19]. Studies on the aftermath of mass casualty events revealed increased levels of anxiety, depression, and post-traumatic stress disorder among healthcare providers, highlighting the urgent need for integrated psychological support systems within healthcare facilities [20]. Thus, resilience training should be embedded within both pre-service education and continuous professional development to ensure sustained coping capacity.

In the Philippine setting, resilience among nurses has been observed as a core strength despite systemic limitations. Community health nurses in disaster-prone areas demonstrate remarkable adaptability, often leveraging local resources and teamwork to manage crises [21]. However, excessive workload, insufficient debriefing, and limited institutional recognition can diminish resilience over time. These findings underscore the need for targeted psychological resilience programs that emphasize mindfulness, peer support, and recovery interventions tailored to Filipino healthcare contexts. Strengthening resilience not only protects nurses' mental well-being but also directly contributes to improved patient outcomes and service continuity during large-scale emergencies.

1.3 Influencing Factors and Institutional Support in Enhancing Disaster Readiness

Preparedness and resilience among nurses are strongly influenced by institutional structures, policy support, and educational interventions. Hospitals with well-established emergency management systems demonstrate higher overall staff confidence and coordination during crises [22]. Institutional investments in simulation laboratories, competency validation tools, and post-event evaluations contribute significantly to improving disaster response effectiveness [23]. Furthermore, continuous professional development programs that incorporate interprofessional collaboration have been found to enhance both preparedness and resilience among nursing personnel [24].

Institutional support also determines how nurses internalize their roles and responsibilities during emergencies. Studies show that organizational culture, leadership communication, and access to mental health resources influence nurses' motivation and decision-making capacity during mass casualty situations [25]. Inconsistent policy frameworks and lack of clear disaster protocols often lead to confusion and delayed response times [26]. A multinational analysis of translational triage models suggests that when supported by clear institutional guidelines, nurses perform with greater efficiency and accuracy during complex emergencies [27]. These findings highlight the critical role of structured policies and administrative preparedness in enhancing clinical performance during disasters.

In developing countries like the Philippines, institutional and governmental support play an even more crucial role in determining nurses' disaster readiness. Research emphasizes that hospitals with limited funding, inadequate equipment, and irregular training sessions face challenges in maintaining consistent preparedness levels [28]. Moreover, ethical and logistical challenges during crisis response—such as resource scarcity and staff shortages—further complicate emergency management [29]. Therefore, establishing standardized national policies, ensuring equitable access to resources, and integrating disaster management training within nursing curricula are vital steps toward improving institutional resilience and overall emergency response efficiency.

II. METHODOLOGY

2.1 Research Design

This study employed a descriptive-comparative research design to evaluate the preparedness and resilience of emergency nurses in disaster and mass casualty situations across public and private hospitals. This design was chosen because it allows for the comparison of measurable indicators of preparedness—such as knowledge and training, emergency response skills, institutional support, psychological resilience, teamwork, and adaptability under pressure—between two distinct groups of nurses. By using a descriptive-comparative approach, the study aims to identify both the strengths and gaps in preparedness and resilience, providing evidence-based insights to inform training, policy, and institutional support initiatives.

2.2 Research Locale and Respondents

The study was conducted among emergency nurses working in selected public and private hospitals within the province. These hospitals were chosen because they have active emergency departments that regularly handle disaster-related and mass casualty cases.

A total of 30 respondents participated in the study, consisting of 15 nurses from public hospitals and 15 nurses from private hospitals. The respondents were selected using purposive sampling, ensuring that only registered nurses currently assigned to emergency or trauma units, with at least one year of clinical experience, were included in the study. This inclusion criterion ensured that participants had relevant exposure and experience in emergency response situations.

2.3 Research Instrument

Data were collected using a structured survey questionnaire designed to measure the perceived preparedness and resilience of emergency nurses in responding to disasters and mass casualty situations. The instrument consisted of two main sections: (1) Demographic Profile, and (2) Indicators of Preparedness and Resilience, which included knowledge and training, emergency response skills, institutional support, psychological resilience, teamwork, and adaptability under pressure.

The questionnaire was adapted from existing standardized tools on disaster preparedness and resilience among healthcare professionals and was modified to fit the local hospital context. The instrument was validated by experts in nursing education and disaster management to ensure clarity, relevance, and reliability of the items. A pilot test was conducted prior to the actual data collection to ensure consistency of responses, and the computed Cronbach's alpha coefficient of 0.82 confirmed that the instrument had high internal reliability.

2.4 Data Gathering Procedures

Prior to data collection, approval was obtained from the institution and hospital administration. The researchers provided a brief orientation to participants explaining the purpose of the study, confidentiality assurance, and their right to withdraw at any time. Upon obtaining informed consent, the questionnaires were distributed personally to nurses during their available duty hours or through online forms, depending on accessibility. The respondents were given one week to accomplish the questionnaire. After the retrieval of responses, the data were checked for completeness and accuracy before encoding and analysis.

2.5 Data Analysis

The gathered data were analyzed using descriptive statistics such as frequency, percentage, mean, and standard deviation to summarize the demographic characteristics and levels of preparedness and resilience among emergency nurses. The results were interpreted using a weighted mean scale to determine whether the nurses' preparedness and resilience were low, moderate, or high. All analyses were conducted at a 0.05 level of significance, and statistical computations were processed using Statistical Package for the Social Sciences (SPSS) software.

2.6 Ethical Considerations

The researchers ensured full compliance with ethical research standards. Informed consent was secured from all participants, who were informed about the voluntary nature of their participation. Confidentiality and anonymity were strictly maintained by excluding any personal identifiers from the survey forms. All collected data were used solely for academic purposes and were stored securely to prevent unauthorized access. The study adhered to the ethical guidelines of the institution and the Philippine Nursing Research Ethics Code.

III. RESULTS AND DISCUSSIONS

Table.1: Hospital Type

Hospital	Frequency (f)	Percentage
Private	15	50%
Public	15	50%
Total	**30**	**100%**

Table 1 shows an equal distribution of respondents between public and private hospitals, with 15 nurses (50%) from each. This indicates that the study captured perspectives from both types of institutions, ensuring that findings on preparedness and resilience are representative of different hospital settings.

Table.2: Frequency and Percentage Distribution of the Respondents in Terms of Gender

Gender	Frequency (f)	Percentage
Male	10	66.7%
Female	20	33.3%
Total	**30**	**100%**

Table 2 shows that the majority of respondents were female, comprising 20 nurses (66.7%), while males accounted for 10 nurses (33.3%). This reflects the common trend in nursing, where female professionals constitute a larger proportion of the workforce, particularly in emergency and trauma units.

Table.3: Frequency and Percentage Distribution of the Respondents in Terms of Years of Experience

Years of Experience	Frequency (f)	Percentage
1-3 Years	10	33.3%
4-6 Years	12	40%
7+ Years	8	26.7%
Total	**30**	**100%**

Table 3 shows that most respondents had 4–6 years of professional experience (12 nurses or 40%), followed by 1–3 years (10 nurses or 33.3%) and more than 7 years (8 nurses or 26.7%). This distribution suggests that the majority of participants had a moderate level of clinical exposure, which may contribute to their ability to handle disaster and mass casualty situations effectively.

Table.4: Mean Scores of Preparedness Indicators

Indicators	Mean	Interpretation
Knowledge & Training	4.10	High
Emergency & Response Skills	3.87	Moderate
Institutional Support	3.73	Moderate
Overall Preparedness	**3.90**	**Moderate**

Table 4 shows the mean scores of preparedness indicators, with knowledge and training receiving the highest rating (4.10, High), followed by emergency response skills (3.87, Moderate-High) and institutional support (3.73, Moderate). The overall preparedness score was 3.90 (Moderate-High), indicating that nurses generally possess sufficient knowledge and skills to respond to emergencies, although institutional support may still need strengthening.

Table.5: Mean Scores of Resilience Indicators

Indicators	Mean	Interpretation
Psychological Resilience	4.00	High
Teamwork	4.13	High
Adaptability Under Pressure	3.90	Moderate
Overall Resilience	**4.01**	**High**

Table 5 shows the mean scores of resilience indicators, with teamwork rated the highest (4.13, High), followed by psychological resilience (4.00, High) and adaptability under pressure (3.90, Moderate-High). The overall resilience score of 4.01 (High) demonstrates that emergency nurses are psychologically stable, capable of effective collaboration, and adaptable when responding to high-pressure disaster scenarios.

Table.6: Comparative Analysis of Preparedness and Resilience Between Public and Private Hospital Nurses

Indicators	Group A	Group B	t-value	p-value	Interpretation
	(Public)	(Private)			
Knowledge & Training	4.00(0.14)	4.20(0.12)	-2.31	0.030	Significant
Emergency Response Skills	3.80(0.16)	3.95(0.18)	-1.65	0.110	Not Significant
Institutional Support	3.60(0.18)	3.85(0.20)	-2.01	0.055	Not Significant
Psychological Resilience	3.95(0.12)	4.05(0.10)	-1.88	0.072	Not Significant
Teamwork	4.05(0.15)	4.20(0.14)	-2.02	0.053	Not Significant
Adaptability Under Pressure	3.85(0.16)	3.95(0.15)	-1.74	0.095	Not Significant

Table 7 shows that private hospital nurses generally scored higher across all preparedness and resilience indicators. Knowledge & training was the only indicator with a statistically significant difference (p = 0.030), suggesting that private hospital nurses may have slightly more access to training or educational resources. Other indicators, including emergency response skills, institutional support, psychological resilience, teamwork, and adaptability, showed higher mean scores in private hospitals but were not statistically significant, indicating comparable levels of preparedness and resilience between public and private hospital nurses overall.

3.7.1.:Knowledge & Training

Table 7 shows that private hospital nurses scored higher in knowledge and training (4.20) compared to public hospital nurses (4.00), with a statistically significant difference (p = 0.030). This indicates that private hospitals may offer more structured disaster preparedness programs, workshops, or simulation exercises, which enhance nurses' theoretical understanding and readiness to act during emergencies. Public hospital nurses, while slightly lower, still scored in the high range, suggesting foundational knowledge is adequate but may benefit from additional practical reinforcement.

These findings are consistent with previous research showing that prior disaster training and simulation-based education significantly improve nurses' preparedness and confidence during mass casualty incidents [7][8]. Structured continuous education is essential to maintain competency and ensure that knowledge translates into effective action during crises [9][10]. Strengthening training opportunities in public hospitals could help bridge the gap in preparedness between different healthcare settings.

3.7.2.: Emergency Response Skills

Table 7 shows that private hospital nurses scored 3.95, slightly higher than public nurses at 3.80, though the difference was not statistically significant (p = 0.110). Both groups exhibited moderate-high competency in performing clinical interventions and responding to emergencies, suggesting that exposure to real-life scenarios and institutional practice supports skill acquisition across hospital types.

This aligns with international studies indicating that emergency nurses' practical skills improve through hands-on experience, triage drills, and prehospital life support training [11][12]. While private hospital nurses may have more frequent access to advanced equipment or simulation exercises, the overall similarity in scores highlights that experiential learning is critical across all settings to maintain effective emergency response.

3.7.3.: Institutional Support

Table 7 shows that private hospital nurses scored 3.85, slightly higher than public nurses at 3.60, though not statistically significant (p = 0.055). This indicates that access to resources, medical equipment, and clearly defined disaster protocols is generally better in private hospitals, providing nurses with a supportive environment to perform effectively during crises.

Prior studies emphasize that institutional support is crucial for disaster preparedness, as it enables nurses to apply their knowledge and skills confidently [7][13]. Public hospitals may face challenges such as limited resources or inconsistent protocols, which can affect performance. Enhancing support systems and resource availability in public settings could help improve overall preparedness and align it with private institutions.

3.6.4.:Psychological Resilient

Table 7 shows that private hospital nurses scored 4.05, slightly higher than public nurses at 3.95 (p = 0.072), with both groups achieving high resilience ratings. This demonstrates that nurses in both settings can manage stress, maintain focus, and recover from emotionally challenging situations during disasters.

This finding is supported by studies highlighting that psychological resilience is essential for nurses to function effectively under high-pressure conditions [14][15]. Interventions such as resilience training, peer support programs, and structured mentoring can further strengthen this capacity, particularly in public hospitals where stressors like understaffing or resource limitations may be more pronounced [16].

3.6.5.: Teamwork

Table 7 shows that private hospital nurses scored 4.20 compared to 4.05 for public nurses (p = 0.053), indicating high teamwork abilities in both groups. Effective collaboration and communication are essential for coordinated response during mass casualty incidents, and both hospital types demonstrate strong team dynamics.

Previous research emphasizes that teamwork significantly affects efficiency, patient safety, and overall disaster response outcomes [7][8][17]. Hospitals with formal disaster protocols and interprofessional training tend to report higher teamwork ratings, highlighting the importance of institutional support alongside individual competency to achieve optimal coordination during emergencies [12].

3.6.6.: Adaptability Underpressure

Table 7 shows that private hospital nurses scored 3.95 while public nurses scored 3.85 (p = 0.095), both falling in the moderate-high category. This suggests that nurses from both hospital types can adjust to unexpected changes, manage multiple tasks, and make timely decisions during high-pressure situations.

This finding aligns with studies showing that adaptability is influenced by both individual coping mechanisms and institutional support [14][18]. Private hospital nurses may benefit from slightly more structured training or resource availability, but overall, both groups demonstrate the capacity to adapt effectively during disaster scenarios. Continuous development programs focusing on flexibility and decision-making under stress could further improve performance across all healthcare settings.

IV. CONCLUSION

Overall, the findings of this study indicate that emergency nurses from both public and private hospitals demonstrate moderate to high levels of preparedness and resilience in disaster and mass casualty situations. Private hospital nurses generally scored higher across most indicators, particularly in knowledge and training, suggesting that structured educational programs, simulation exercises, and resource availability contribute to enhanced readiness. Both groups, however, exhibited strong psychological resilience, teamwork, and adaptability under pressure, reflecting their ability to function effectively in high-stress environments. Institutional support emerged as a relative area for improvement, especially in public hospitals, highlighting the need for consistent protocols, adequate resources, and continuous professional development. These results underscore the importance of combining individual competency, practical training, and organizational support to ensure optimal emergency response, ultimately enhancing patient outcomes and overall healthcare system resilience.

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International Journal of Advanced Engineering Research and Science (IJAERS)
Peer-Reviewed Journal
ISSN: 2349-6495(P) | 2456-1908(O)
Vol-12, Issue-10; Oct, 2025
Journal Home Page Available: https://ijaers.com/
Article DOI: https://dx.doi.org/10.22161/ijaers.1210.9

Exploration of the Development and Technical Features of Intelligent Inspection Robots

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Received: 25 Sep 2025,
Received in revised form: 23 Oct 2025,
Accepted: 27 Oct 2025,
Available online: 31 Oct 2025

***Keywords*— Inspection robot, development trend, technical characteristics**

***Abstract*— With the development and advancement of The Times, industrial intelligence has flourished, and the emergence of inspection robots has made significant contributions to the inspection methods of the working environment in many production enterprises. Many enterprises have adopted inspection robots instead of manual inspection, which plays a significant role in achieving industrial chain upgrading and transformation. This paper compares the development trends of inspection robots at home and abroad, studies the motion structures and countermeasures of different inspection robots in different environments, analyzes the technical characteristics and advantages of inspection robots, makes corresponding measures and solutions based on the current industry situation, and explores the innovation and development trends of inspection robots in the future.*

I. INTRODUCTION

With the flourishing of robotics, we are entering a new era of full intelligence. Intelligent robots, with their outstanding performance, precise control and powerful learning ability, are gradually penetrating into all areas of production and life. These robots not only produce a wide variety of types to meet the needs of different industries and scenarios, but also greatly improve work efficiency, reduce labor costs, and significantly enhance safety and reliability. At the same time, intelligent robots are produced on a large scale and are important equipment for realizing the digitalization, networking and intelligence of industrial production. Their research and development, manufacturing and application are also important indicators[1] of a country's level of scientific and technological innovation and high-end manufacturing.

Inspection is an important means to ensure the safety of production, operation or service processes. In the daily management of all kinds of facilities, equipment, and even the natural environment, inspection can detect and eliminate potential safety hazards in a timely manner, effectively curb the occurrence of safety accidents, and ensure the safety[2] of people's lives and property. Secondly, through regular inspections, one can understand the operation status of equipment and facilities, carry out timely maintenance and upkeep, extend their service life, ensure that everything operates in order, and at the same time respond quickly to abnormal situations, reduce losses, and improve the safety and stability of the overall operation.

At present, traditional manual inspection is the main form of inspection in domestic enterprises, but manual inspection cannot guarantee that the inspectors are in place and there are many problems[3]. Manual inspection is time-consuming and labor-intensive, and is prone to incomplete or incomplete inspections due to fatigue and negligence. In addition, environmental factors such as bad weather and complex terrain can also pose safety hazards[4] to inspectors. Moreover, the data recording and processing of manual inspection are often subjective and inaccurate, making it difficult to ensure the objectivity and reliability[5] of the inspection results.

Nowadays, automated and intelligent inspection methods are gradually becoming a trend. Intelligent inspection systems connect to devices such as sensors and cameras to monitor[6] the status of equipment in real time, collect operational data such as temperature, pressure, vibration, etc., process and analyze[7] the data through software systems to identify potential safety hazards and faults, and generate inspection reports for managers to refer[8] to. In addition, the intelligent inspection system can automate inspection tasks, significantly reducing labor costs and time consumption, and significantly improving work efficiency[9]. Among them, intelligent inspection robots have significant advantages in improving inspection efficiency, precise detection, ensuring personnel safety, reducing labor costs, real-time data transmission and decision support, as well as autonomous learning and optimization, and have become a relatively reliable inspection method in today's society.

Intelligent inspection robots are highly flexible and adaptable in technology, capable of handling a wide range of complex and variable inspection tasks[10]. Meanwhile, advanced technologies such as communication technology, artificial intelligence, Internet of Things, and hybrid cloud are widely applied in various fields, providing technical support[11] for the development of intelligent inspection robots. As a result, from fire warning[12] to building troubleshooting[13], from security monitoring[14] to space operation and maintenance[15] , intelligent inspection robots are gradually replacing traditional manual inspection methods with their unique advantages. This trend of intelligence has not only driven technological advancements in intelligent inspection robots, but also injected new vitality into the development of modern industry.

II. TRENDS IN THE DEVELOPMENT OF INSPECTION ROBOTS

2.1 Trends in Inspection Robots Abroad

Research and application of inspection robots abroad started earlier than in China. The first industrial robot[16] was developed by American Joseph Engelberger in 1959 using the patent technology authorized by George Devol in 1954. In other different fields, inspection robots have also been gradually applied abroad. However, in the power industry, the research and application of intelligent inspection robots are most mature. As early as 1980, inspection robots were already being used abroad to detect[17] heat-induced defects in substation equipment. In the 1990s, Tokyo Electric Power Company and Mitsubishi Corporation of Japan jointly developed substation inspection robots, using infrared thermal imagers and digital image acquisition devices to obtain information[18] within substations; In 2008, the University of Sao Paulo in Brazil developed a mobile inspection robot for temperature monitoring inside substations, which is small in size and weight and easy to operate. The infrared thermal imager moves[19] along a high-altitude track set up above the substation. As a result, the development and research of inspection robots abroad have been constantly updated and improved, from the early two computers controlling one simple robot to the current advanced robot[20]. In the 21st century, inspection robot technology abroad has now reached the level[21] of commercial industrialization in areas such as security inspection, home services, and power inspection.

2.2 Development of inspection robots in China

Compared with the development of inspection robots in foreign countries, China's research on intelligent inspection robots started relatively late, but has developed very rapidly. The state has a lot of policy support in this field. In recent years, the state has vigorously implemented automated and mechanized working methods, and inspection robot technology has developed rapidly in China. This has led to the design and development of low-cost, efficient and reliable intelligent inspection robots, which have been widely used in inspection and monitoring, thus better replacing manual inspection methods. The Ministry of Industry and Information Technology's "Notice on the 14th Five-Year Plan for the Development of the Robot Industry" points out that "in the face of new situations and new requirements, the next five years and beyond will be a strategic opportunity period for China's robot industry to achieve self-reliance and leapfrog development." We must seize the opportunities, face the challenges, accelerate the resolution of problems such as insufficient technological accumulation, weak industrial foundation and lack of high-end supply, and push the robot industry towards the medium-high[22] end.

Research on inspection robots in China began with substation inspection robots in Shandong Province in 1999. The idea of using mobile robot technology for equipment inspection in substations was first proposed in 2001, and the first domestic product prototype was developed and applied in the 500kV inspection operation[23] of Changqing Substation in October 2005. After years of research, intelligent inspection robots have gradually achieved certain development results, especially in the application[24] of intelligent inspection robots in substations of the power industry. An active disturbance rejection control (ADRC) architecture[25] based on data-driven method compensation is proposed, for example, in response to the problem that inaccurate control input matrices can affect control performance in the ADRC system of substation inspection robots. A lidar-based inspection robot system was studied in response to the complex environment of substations, the high intensity and low efficiency of manual inspection. The environment map was established using the laser Simultaneous Localization and Mapping (SLAM) algorithm, and real-time localization was carried out using the Adaptive Monte Carlo localization (AMCL) algorithm in combination with laser and odometer data. For the substation environment, inspection coordinates and key points in the path were marked on the map, and global path planning and point-to-point navigation algorithms[26] were designed.

Nowadays, industrial development is rapid and society is gradually entering the intelligent era. Artificial intelligence technology exists in the production equipment of numerous manufacturing enterprises, with a wide variety of types and large demands. It is also used in a wide range of different fields, such as the application of inspection robots in utility tunnels, the research[28] and application[27] of intelligent inspection robots in offshore oil fields, and the study[29] of suspended track-type intelligent inspection robots. To use the intelligent inspection robot efficiently and safely, we need to develop a complete control system that enables it to navigate through its positioning system, automatically collect information, and detect problem points. Monitor the inspection robot via wireless network, process the collected images, automatically alarm abnormal points, automatically notify daily inspectors to go to the occurrence site for confirmation and prompt handling, thereby achieving efficient and reliable intelligent inspection results.

Looking at the development status of domestic intelligent inspection robots, intelligent networking is a good carrier. Intelligent inspection robots achieve intelligence through the Internet and their own computing. For example, before working, intelligent inspection robots need to know the status of nearby devices through the Internet, and some devices need to be inspected with focus. When faults are detected, the information is integrated and processed through the Internet and finally sent to robot terminals or human terminals with other functions. Then proceed to the next step. The connected system of the intelligent inspection robot is like the human body system, in which the intelligent inspection robot plays the role of the "nerve center", and the Internet and other mobile terminals are the "blood

vessels" of the "nerve center", and the "blood" carried in it continuously provides "nutrition" for the intelligent inspection robot to work efficiently and accurately. Networking is a product of the development of the Internet of Things and a concrete manifestation of it. From a broader perspective, connectivity will drive the upgrading and transformation of the robotics industry[30] and become the most promising development trend today.

III. DESIGN OF THE MOTION STRUCTURE OF INSPECTION ROBOTS

3.1 Ground inspection robot

3.1.1 Wheeled inspection robot

A wheeled inspection robot is an automated robot that uses wheels as a means of movement and is primarily used for monitoring and inspecting various facilities and infrastructure. The advantage of the wheeled inspection robot over other robots lies in its simple structure, high flexibility, fast movement speed, wide range of movement, high degree of autonomy, and suitability for flat and open roads[31]. With the acceleration of urbanization, traffic tunnels have become an important part of the modern transportation network. However, due to the complex and changeable internal environment of tunnels, traditional manual inspection methods are difficult to meet the requirements. Therefore, Chen Guocui et al. have proposed a new type of tunnel wheeled inspection robot. The wheeled inspection robot uses a multi-wheel independent drive walking mechanism to achieve all-round flexible movement, and it ensures continuous contact between the wheel-ground contact surface and the tunnel profile through active suspension technology, guaranteeing the robot's ability[32] to pass. Likewise, for the special working environment in coal mines and coal washing plants, Li Pengcheng et al. have designed a wheeled drive inspection robot suitable for narrow Spaces. This robot uses two-wheel differential drive and is small in size, which can ensure smooth cornering and flexible passage through narrow Spaces[33]. The wheeled chassis structure of the wheeled inspection robot produced by CITIC Heavy Industries Kaicheng Intelligent Equipment Co., Ltd. not only has the basic functions of the above wheeled inspection robot, but also has excellent climbing and obstacle-crossing capabilities[34] .

There is also a wheel-legged inspection robot based on the wheel-mounted inspection robot, which can work flexibly in various terrains. The detachable wheel-legged quadruped inspection robot designed by Dou Yuhuan et al. takes advantage of the wheel-legged inspection robot. It can flexibly switch operation modes according to the actual environment of the mine and also improves the stability[35] of the robot. In addition, the McNam wheel inspection robot is also widely used. TheMcNam wheel inspection robot is an omnidirectional mobile robot platform based on the McNam wheel. Each wheel is equipped with a 45-degree bevel roller, which allows the robot to move and rotate freely. Some designers have created the McNam wheel inspection robot, which takes advantage of the high[36] degree of freedom of the McNam wheel. This McNam wheel inspection robot has the ability[37] to move in all directions and can move and rotate freely in narrow Spaces or environments with dense obstacles. Therefore, it is often used in industrial environments where mechanical equipment, pipelines, etc. need to be inspected frequently.

3.1.2 Crawler-type inspection robots

A tracked inspection robot is an automatic or remote-controlled robot with a tracked drive system, often used for inspection tasks in complex or harsh terrain. Tracked patrol robots have a significant advantage over wheeled patrol robots. Tracked patrol robots can move stably on uneven, rough or soft surfaces such as muddy, sandy, snowy or stony ground. The tracks provide the robot with a large ground contact area, reducing the pressure per unit area, allowing the robot to move on soft ground without getting stuck. The multimodal intelligent tracked inspection robot designed by Li Minghao and others takes advantage of the tracked inspection robot, with a tracked chassis that enhances the inspection robot's ability[38] to handle complex road conditions. Tracked inspection robots are often equipped with multi-functional accessories such as robotic arms, cameras, sensors, etc., and can perform various tasks such as inspection, monitoring, grasping, and repair. The tracked inspection robot with an auxiliary wheel swing arm, designed by An Zhiguo et al., is simpler in structure, smaller in size and lighter in weight compared to previous tracked inspection robots. It has better obstacle-crossing and grasping capabilities and can perform multiple tasks[39] simultaneously.

The chassis tracks in the tracked inspection robot are an important advantage of this robot. The tracks are placed parallel to the ground, providing a wider support base surface. Therefore, compared with wheeled inspection robots, the tracked inspection robot can easily climb slopes or cross obstacles such as stones, broken wood, etc., and it can also remain stable on steeper slopes or unstable ground. For example, the current oil and gas pipeline robots have problems such as weak adaptability to oil and gas pipelines and poor climbing ability. Yu Jiuyang et al. have proposed a tracked oil and gas pipeline inspection robot that can change diameter. The inspection robot is mainly used in chemical pressure pipelines, crude oil, refined oil and natural gas transportation pipelines. It can perform intelligent inspection functions on special equipment such as pressure vessels and pressure pipelines in chemical equipment in industries such as chemical engineering, oil and gas, and nuclear power. It can also climb 45-degree and 90-degree slopes[40] while bearing its own weight. Tracked inspection robots typically consume more maintenance and energy than wheeled ones because of their structure and drive mode. But tracked patrol robots can reach hard-to-reach areas, and the value of performing tasks often outweighs the additional cost. As Han Long etal. designed, the tunnel crawler inspection robot is used in narrow tunnels that are difficult for workers to access. It can not only move steadily within the tunnels but also transmit real-time information[41] about the tunnels.

3.2 Underwater inspection robot

Underwater inspection robots are a type of robot that can independently or remotely perform inspection, detection, maintenance and other operations in underwater environments. They are widely used in the fields of underwater facility inspection, water quality monitoring, Marine biological research, and diving rescue assistance. In response to the complex underwater environment, Favor Oluwatobi Adetunji et al. delved into the challenges associated with navigation and maneuverability in remotely operated ROV (ROV) teleoperation and introduced an underwater digital twin (DT) system aimed at enhancing underwater teleoperation, enabling autonomous navigation, and supporting system monitoring. And through simulation to facilitate system testing, the situational awareness of remote operators was enhanced and their workload[42] was reduced. To address the energy consumption problem, Fu experimentally established the correspondence between different swimming postures of robotic fish and energy consumption in the flow field environment, and used reinforcement learning algorithms to optimize the swimming postures with the least energy consumption of fish in the flow field, achieving energy savings[43] in group movement. Regarding how to obtain underwater images without dehydration and how to analyze wear through images, Li Yonglong et al. developed a novel underwater inspection system, UIS-1, and designed an integrated component for the underwater robot, which partially removed silt and obtained images of the concrete surface of the still water pool plate at the desired position; Secondly, an image algorithm was proposed to obtain the aggregated exposure rate for quantitative wear analysis[44] .

3.3 Aerial Inspection Robot

An aerial inspection robot is typically an unmanned aerial vehicle equipped with high-definition cameras and advanced sensors. They can fly autonomously and perform environmental analysis and data collection through built-in computer systems and artificial intelligence algorithms. These robots are primarily used for quick and efficient inspections of every corner of the city. To alleviate the problems of poor route planning and low cruise efficiency of unmanned aerial vehicle (UAV) power inspection, and to avoid the threat of unreliable paths, Chang An et al. proposed research methods for intelligent route planning and autonomous inspection of UAV power inspection, which improved the autonomous inspection effect, route planning effect and cruise efficiency[45] of UAVs. Zhuo Haoze et al. proposed a drone pose estimation method based on point-line feature fusion in the transmission line scene, which solved the problem of poor robustness of traditional drone visual odometry, enabling drones to efficiently extract point and line features in infrared images and have stronger robustness[46] in weak texture and sudden light changes environments.

IV. FEATURES OF ROBOTICS TECHNOLOGY

4.1 Autonomous Path planning

Autonomous path planning is the automatic planning of an optimal or suboptimal path from the starting point to the destination point by a robot or unmanned system without external guidance based on its own sensor data and preset algorithms. It is a core component of robotics technology.

The various algorithms that enable robots to achieve autonomous path planning each have their own advantages, but there are still some areas that need improvement. For example, the RRT algorithm requires a lot of iterations to find the path, so the time cost of the entire process is relatively high. Yu Qiang et al. conducted a study on path planning based on the MI-RRT^ (*) (Modified Informed RRT^ (*)) algorithm. By introducing greedy sampling and adaptive step size methods, they improved the convergence rate of the algorithm and reduced the path generation time[47] . Path planning for mobile robots in complex environments faces problems such as insensitivity to the environment, low efficiency, and poor path quality of the fast-extended RRT algorithm. In 2023, a CERRT algorithm was proposed by scholars, and simulation results showed that CERRT performed better than RRT and RRV algorithms[48] in complex environments such as mazes and narrow passages. In the factory sector, the increasing labor costs make it difficult for factories to recruit employees to perform manual operations. Zhang Yu et al. proposed a GFS RRT^ (*) -SMART algorithm for global path planning and a deep reinforcement learning hybrid behavior evaluation (MAC) algorithm for obstacle avoidance decisions in local obstacle avoidance, enhancing the robot's performance[49] in sharp turns. In some cases, the computational cost of the A* algorithm can be very high. And factory safety checks are crucial for maintaining a safe production environment. At present, inspections are mainly carried out manually on a regular basis, resulting in low efficiency and heavy workload. Some scholars have proposed A hybrid path planning algorithm that combines the A-star algorithm and the time elastic band algorithm to address the problem of path planning getting stuck in local optimum in complex environments and improve the detection efficiency[50] of robots. Some scholars have proposed an ASL-DWA (A Star Leading Dynamic Window Approach) algorithm compared to the traditional A-star algorithm, which searches for more nodes, resulting in broken paths that cannot.avoid local unknown obstacles. And a mechanism was designed to adaptively adjust the coefficient based on the distance between the robot and the target point, thus achieving ASL-DWA. Compared with traditional algorithms, the ASL-DWA algorithm can meet the path planning requirements[51] of mobile robots in indoor environments.

4.2 Visual image recognition

Visual image recognition is an artificial intelligence technology that enables computers to "see" and understand visual data by imitating human visual perception. At present, visual image recognition technology still faces many challenges such as complex backgrounds, lighting and scale variations, and real-time performance. In 2010, Wen Feng et al. studied SLAM algorithms for monocular vision by fusing visual information with odometry information using extended Kalman filters to improve the accuracy of robot positioning and mapping. [52]In addition, visual object detection and segmentation have been an important research area for autonomous driving environment perception, but mainstream object detection and segmentation algorithms have problems such as low detection accuracy and poor mask segmentation quality for multi-object detection and segmentation in complex traffic scenarios. Some scholars have improved the Mask R-CNN by replacing the backbone network ResNet with the ResNext network with group convolution, further enhancing the model's feature extraction ability.[53]

Wildfires have a negative impact on forest biodiversity and human life. It spreads so fast that early detection of smoke and fire plays a crucial role in improving the efficiency of firefighting operations, but the different shapes, sizes, and colors of smoke and flames make their detection a challenging task. In 2024, scholars employed the latest YOLO algorithm for detecting and locating smoke and wildfires in ground and aerial images. The YOLOV7X model outperformed the baseline model in detecting both smoke and wildfires, while the YOLOV8S achieved[54] some success in identifying and locating wildfire smoke alone. The development of educational robots holds great promise in the field of education, as they can interact with students in learning environments and provide personalized educational support for students. However, object detection in complex environments remains challenging because classrooms or learning scenarios involve various objects, backgrounds, and lighting conditions. In 2024, scholars proposed a brain-inspired heuristic approach for educational robot object detection that integrates Faster R-CNN, YOLOv3, and semi-supervised learning to improve the accuracy and efficiency[55] of object detection in educational robot systems.

4.3 Communication Control System

4.3.1 Remote control and monitoring

Remote control and monitoring refers to the technology of operating, managing, and monitoring remote equipment, systems, or processes through a network or other means of communication, allowing users to control and monitor the target object away from the actual operation site. Although significant progress has been made in remote control and monitoring technology, there are still certain limitations such as security issues, real-time requirements, data processing and analysis, etc.

In response to the complex information and unstable collaboration in multi-robot remote monitoring systems, Liu Xin et al. proposed a hierarchical architecture for shared control systems based on multi-Agent technology, and designed a hybrid Agent architecture for the characteristics of teleoperation systems. The practicability and effectiveness[56] of the hybrid Agent architecture were verified through experiments.

For the special application environment of the substation, there are certain requirements for the operational reliability, parking positioning accuracy and anti-interference ability of the inspection robot. Zhu Xingke et al. designed a motion control system for a substation inspection robot. Through magnetic trajectory guidance and RFID positioning, as well as the technology of differential speed of two drive wheels and follow-up of two swivel wheels, the posture and position of the robot body were determined respectively, and motion control instructions were executed to meet the application requirements[57] of the substation inspection robot. Sun Dihua et al. proposed a HSIC-Smith control algorithm to improve the dynamic performance of the teleoperation system of the inspection trolley in response to the shortcomings of the current control schemes for the network delay variation problem, such as the contradiction between stability and operability, excessive reliance on the model accuracy of the controlled object and poor anti-interference ability. Compared with the conventional PID-Smith pre-estimation method, this algorithm enables rapid and accurate teleoperation control of the inspection trolley system under the condition of network delay variation, and has strong adaptability[58] to the change of network delay.

4.3.2 Fault Diagnosis and Alarm

In robotics technology, fault diagnosis and alarm is a process that involves monitoring the operational status of robots, detecting and identifying potential faults or abnormal situations, and issuing alarm signals to enable timely measures to be taken for handling. Although fault diagnosis and alarm technology is widely used in the field of robotics, it still faces challenges due to the limitations of sensor technology, the complexity of fault models, and the adaptability of diagnostic algorithms. Zhao et al. obtained estimates close to the real model state through UKF filtering to determine the type of sensor fault. Experimental comparisons with traditional FSMM methods show that this method can effectively determine the fault types of individual or combined sensors in mobile robots and significantly improve diagnostic accuracy[59]. By placing various corresponding sensors on the medical devices that needed to be monitored, Huangfu Dejun et al. achieved pre-scheduling of medical device failures and enhanced emergency response capabilities. He developed a medical equipment inspection monitoring and alarm system to improve the traditional medical equipment supervision system and enhance the intelligent inspection effect[60] of medical equipment.

V. CONCLUSION

With the continuous improvement of safety management standards in modern industry and the rapid development of science and technology, intelligent inspection robots, as an intelligent auxiliary tool, are gradually becoming the backbone of safety, environmental protection, and data-driven management. At present, intelligent inspection robots have demonstrated their unique advantages and potential in various scenarios such as pipe galleries, tunnels, and substations, but their widespread application is still insufficient and their diversified development is in urgent need of improvement. Many enterprises still rely on traditional manual inspection methods, which are not only limited by issues such as labor costs, efficiency and safety, but also difficult to meet the urgent demands of modern industry for efficiency, accuracy and intelligence. At the same time, although inspection robots on the current market have certain autonomous navigation, data collection and analysis capabilities, their adaptability, stability and intelligent decision-making capabilities still need to be enhanced in complex and changeable working environments. With the continuous maturation and integration of technologies such as artificial intelligence, the Internet of Things, and big data, intelligent inspection robots will have a much broader space for development. More innovative inspection robot products will emerge in the future, which will have stronger autonomous learning ability, higher environmental adaptability and wider application scenarios, and be able to accurately identify potential safety hazards in complex environments and achieve efficient inspection and intelligent diagnosis. Meanwhile, with the popularization of technology and the reduction of costs, intelligent inspection robots will gradually become an indispensable part of enterprise safety production and operation and maintenance management, driving the entire industry towards a more intelligent and unmanned direction. This will not only greatly enhance the production efficiency and safety of enterprises, but also contribute more to the sustainable development of society.

ACKNOWLEDGEMENTS

This work described in this paper was supported by The Research Funding Of GDUPT, Lagrangian Coherent Structure Analysis of Heat Sink for Heat Transfer Performance with Piezoelectric Fan, Guangdong Science and Technology Program, (Project No. 2024A0505050022), the Research Funding of GDUPT, Axis Intelligence AI -μBayes - A bearing fault diagnosis system for the petrochemical industry based on Micron-level CNN-LSTM (Project No.25A018), and the Research Funding of GDUPT, Horizon Patrol - Machine Inspection Expert Driven by YOLOV8 Engine (No. 71013513124014).

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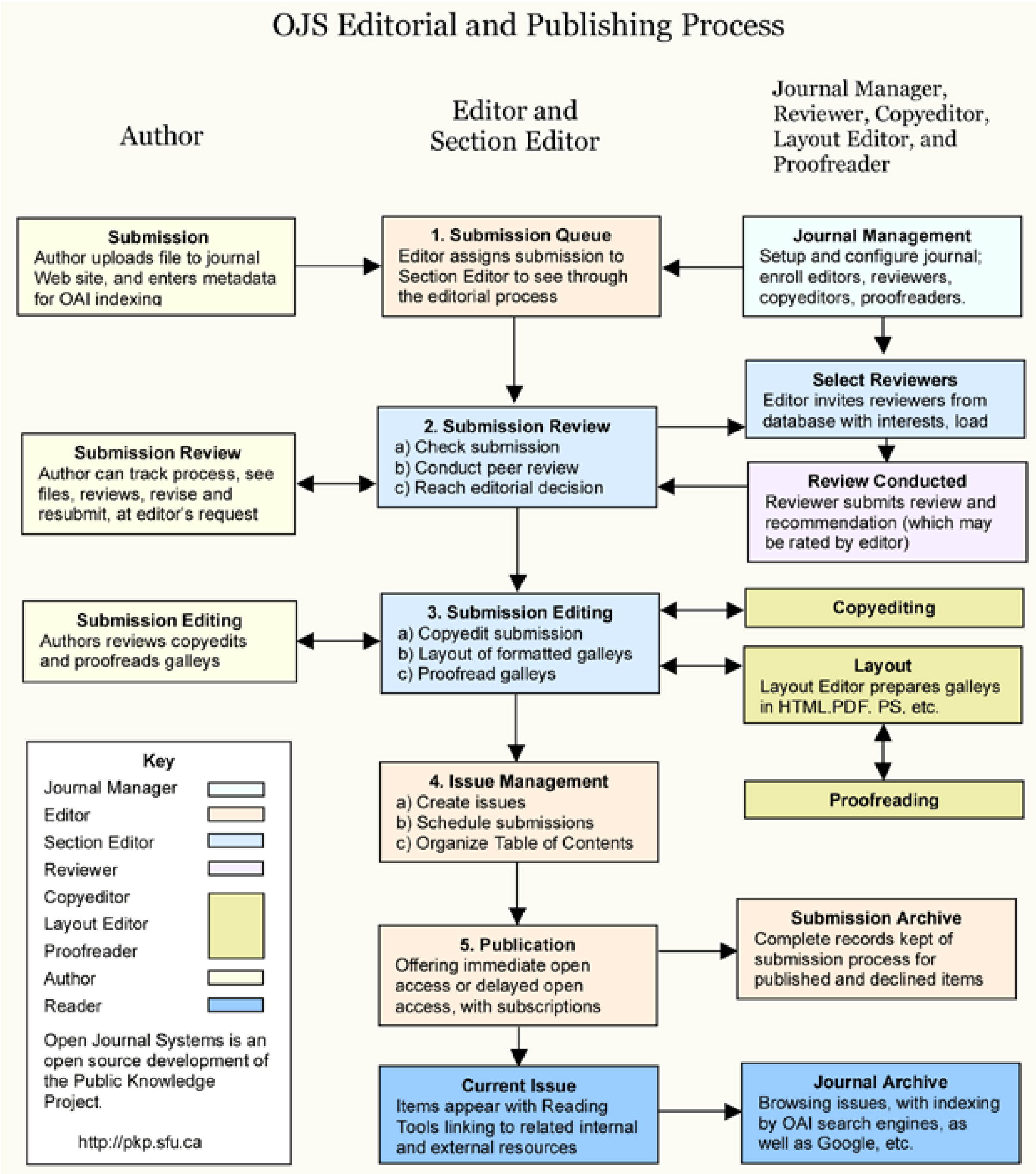

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