
JESTT
Vol. 3, Issue. 2, 2026
SCOPUA

Journal of Engineering, Science and Technological Trends

ISSN(p): 3136-2095

ISSN(e): 2959-1937

Volume 3 (Issue 2) Published on 2026-07-10

https://doi.org/10.64060/JEST3i2

2026

Journal Homepage

https://journals.scopua.com/index.php/JeSTT

Publisher

Scientific Collaborative Online Publishing Universal Academy

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Journal of Engineering, Science and Technological Trends

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Journal of Engineering, Science and Technological Trends (JESTT) aims to advance the understanding of engineering sciences by providing a platform for the publication of unique contributions in the field of engineering, science, and technology.

The scope of the Journal of Engineering, Science and Technological Trends was interdisciplinary. During the board meeting on February 28, 2025, the scope of JESST was redefined to explicitly focus on "Materials Science and Engineering", "Nanoscience and Nanotechnology", "Environmental and Applied Engineering", "Computational and Data-Driven Approaches", and "Cybersecurity and Smart Systems".

The updated scope reflects our commitment to publishing high-quality, original, and innovative research that addresses contemporary challenges and advances theoretical and applied knowledge within the journal's core disciplines. JESTT welcomes manuscripts in both fundamental and applied research areas and encourages submissions that contribute novel and innovative insights to engineering science and technology. The scope of JESTT includes:

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- Artificial Intelligence in Cybersecurity
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Journal of Engineering, Science and Technological Trends (JESTT)

Vol. 3, Issue 2, July 2026
DOI: https://doi.org/10.64060/JESTT3i21

Article

Stimuli-Response in Organic Cocrystals with Different Donor-Acceptors

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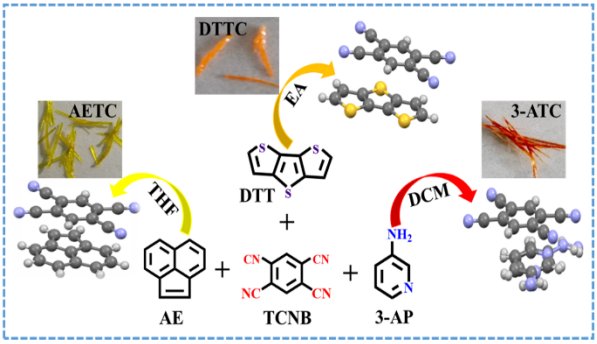
Received: 26 January 2026 / Revised: 23 February 2026 / Accepted: 15 March 2026 / Published online: 11 May 2026

ABSTRACT

Organic cocrystal engineering refers to the stoichiometric combination of two or more organic molecules through non-covalent intermolecular interactions, but achieving excellent electrical and optical properties remains a challenge due to the lack of clear directions for the rational design of co-crystals. In addition, herein we compare and report these three new cocrystals' chemical and physical properties, crystalline structures and determined response to acid stimuli. This investigation of organic cocrystals contains intermolecular interactions and growth methods, especially the solvent evaporation approach. As a result, we synthesised three new organic cocrystals; among these cocrystals, 3-ATC has the highest response to acid stimuli (different acid fuming). The cocrystal's response time is also in the order of seconds, which is much faster than that of most other stimuli-responsive cocrystals previously described. 3-ATC is a highly sensitive fluorescence switching exhibited under various acid stimuli. But, the other two cocrystals (AETC and DTTC) are strong enough to resist acid stimuli; this is due to the close face-to-face and mixed stacking patterns with CT and π-π interactions. These three cocrystals exhibited different colours and low-dimensional (1D, 2D) morphology structures.



Keywords: Acid stimuli; Cocrystal growth; CT interactions; Organic cocrystals; Solvent evaporation

1. Introduction

In recent years, there has been an increasing demand for multifunctional materials. Cocrystal engineering is a method that prepares new materials with unique optical and electrical properties using non-covalent bond interactions. This method has gained significant attention [1],[2]. Cocrystallized organic molecules with alkali, alkaline earth salt, inorganic acid, and halogen include haloquinone. The majority of organic cocrystals contain aromatic compounds, including dinitro or Trinitro. It is interesting to note that many cocrystals were discovered by different advanced screening techniques in the 1900 century; some of these have been discovered by scientists in interesting ways [3]. Organic cocrystals have a wide range of applications, including organic field effect transistors (OFETs) [4], photoresponse [5], organic light-emitting transistors (OLETs) [6], room temperature phosphorescence [7], two-photon absorption properties [8] and so on. However, selecting suitable molecules to prepare cocrystals with novel properties is still a great challenge [9]. The organic crystal research field is currently focusing on figuring out how to customise CT and predict the function of cocrystals. Previous studies have mainly focused on selecting the appropriate building blocks to alter the static characteristics of cocrystal formations [10]. Among these, cocrystals made up of easy-to-withdraw acceptors and powerful electron-donating donors are frequently shown to have CT interactions. It is possible to control their activity by mixing various donor and acceptor molecules [11]. At present, the solution approach is the most widely used technique for the

preparation of organic cocrystals [12],[13]. the physical vapour transport (PVT) method [14] and mechanochemical preparation [15]. Different preparation methods allow the preparation of cocrystals with different morphologies, structures and properties. The dissolution method has the advantages of simple operation, flexible design and low cost [16]. In theory, the molecular units of organic cocrystals can be assembled in any molar ratio, but in the existing cocrystal system, the most common are two constituent units and the molecular molar ratio is 1:1 [17]. Designing organic cocrystals with appropriate physical and chemical properties requires an understanding of intermolecular interactions and their influence on crystal stacking. The interactions between different molecules in cocrystals have a non-negligible effect on the properties of cocrystals. Supramolecular interactions in organic cocrystals include charge transfer interactions, π-π interactions, hydrogen bonds, and halogen bond interactions [18]. However, a variety of preparation techniques enable the production of cocrystals with varying morphologies, topologies, and characteristics [19]. The stimulus-responsive behaviours of single-component molecules have been widely studied. However, the investigation of multiple components is still in its primary stages due to the unclear mechanism of cocrystallisation and the uncontrollable functions of the final products. Scientists discovered that the crystal-to-crystal transition between two polymorphs can offer a natural illustration of how to understand the process under the stimuli-responsive mechanism. A timely and insightful study of organic cocrystals toward functional materials is presented, which is expected to open up a new design principle of functional materials for practical applications [20],[21]. In addition, external stimuli can alter intermolecular interactions and even stacking structures, and the degree of CT interaction in cocrystals can be verified and adjusted through experimental methods [22]. A molecular-level structure performance relationship can be established based on organic CT cocrystals to reveal the response mechanism and guide smart cocrystal development.

Herein, we designed and prepared three new organic cocrystals, wherein the TCNB as electron acceptors (A), and three different (AE, DTT and 3-AP) electron donors (D), these cocrystals displays a mixed-stacking arrangement with strong intermolecular interactions, which contributes to the CT nature over the whole supramolecular architecture. Meanwhile, among these cocrystals, the 3-AP molecule in 3-ATC cocrystal can easily interact with the proton because of the weak alkaline nature of their 3-Amide and pyridyl groups, while the degree of CT interactions in 3-ATC can be adjusted by adding electron-withdrawing electropositive hydrogenations. As a result, 3-ATC may respond to various acidic environments and stimuli to change its emission characteristics dynamically (emission colour from red to cream-white; photoluminescence quantum yield from high to low). But the other two cocrystals, AETC and DTTC, were stable against acid stimuli. Therefore, by carefully designing each component, we show how to create an adjustable luminous switching cocrystal system that can be dynamically regulated in response to various acid stimuli. This illustrates the ideal method for creating next-generation smart and multiple functional materials [23]. In addition, those cocrystals in a TCNB-based CT complex system are nearly planar, and stacked alternately on each other, which prompted us to investigate whether the co-assembly of CT complexes with similar acceptor and different donors' structures would emit in yellow, orange and red colours [11].

2. Material and Method

2.1. Materials

AE (C12H10, 98%), DTT (C8H4S3, 98%), 3-AP (C5H6N2, 99%), and TCNB (C10H2N4, 98%) were the pure single materials, purchased from Shanghai Energy Chemical Corporation, Ltd and Tianjin Xiensi Opod Technology Co., Ltd respectively. Dichloromethane (CH2Cl2), tetra-hydrofuran (THF) and ethyl acetate (EA) were purchased from Tianjin Yuanli Chemical Co., Ltd. Formic acid, Acetic acid, and Hydrochloric acid (HCOOH, CH3COOH, and HCl) solutions were purchased from Tianjin Comeo Chemical Reagent Co., Ltd. and Tianjin Yuanli Chemical Co., Ltd., respectively.

2.2. Crystal Growth and Characterisation

The crystal growth process is provided in the supplementary file. After designing and preparing the cocrystals, we investigated and determined their physicochemical properties, performed structural analysis, and carried out further characterisation. Powder X-ray diffraction (PXRD) measurements were conducted using a Rigaku SmartLab diffractometer. Testing parameters: Cu Ka radiation, λ = 1.5418 Å, the power was set to 9 kW, the voltage was 45 kV, and the current was 200 mA. The single-component molecules (AE, DTT, 3-AP, and TCNB) with 5-45 degrees, and the angle interval was 0.01, so PXRD's spectra showed that the organic cocrystals have good quality. The sharp peaks of the cocrystals in PXRD revealed the high quality of the single crystals and the presence of AETC, DTTC, and 3-ATC organic cocrystals, demonstrating that these co-assembled into cocrystals completely during the PVT process.

To determine the structure of the cocrystals, single crystals suitable for X-ray diffraction were chosen, mounted in inert oil in the cold gas stream, and their X-ray diffraction intensity data were collected. On a Rigaku XtaLAB FRX diffractometer equipped with a Hypix6000HE detector, using Cu Kα radiation (λ = 1.54184 Å). Crystal was kept at the temperature listed in the X-ray crystallography section during data collection. The structure was solved by the intrinsic phasing method using SHELXT and then refined with SHELXL in Olex2. Selected details of the data collection and structural refinement can be found within the X-ray crystallography section and full details are available in the corresponding CIF files.

Moreover, crystalline silicon wafers were utilised as the substrate in an optical microscope (OM). Silicon wafers' high atomic-plane structure and clarity made them ideal materials for photographing tiny particles. They are available in several shapes and sizes, and we used the Si-III silicon wafers with sizes of 5 mm × 7 mm and dissolved the same ratio 1:1 molar parent material, i.e., donors and acceptor, in DCM, THF, and EA. The D-A mixture was prepared, and two drops of the solution were applied to a silicon wafer. The OM was utilised to observe and analyse the resulting cocrystal's morphology.

The solid-state samples of the AETC, DTTC, and 3-ATC cocrystals were used for the investigations and determination of photophysical and chemical properties. We used a variety of instrument measurements, including UV-vis, photoluminescence (PL), thermal gravimetric analysis (TGA), differential scanning calorimetry (DSC), and Fourier-transform infrared (FTIR).

The UV-3600 Plus (SHZMADZU, Japan) spectrophotometer, combined with a diffuse reflectance mode integrating sphere, was used for testing the UV-visible diffuse reflectance spectrum. The small amount of powder under the test was evenly applied to the Barium sulfate ($BaSO_4$) substrate. A baseline test of the blank $BaSO_4$ was required to eliminate substrate effects before testing the sample. Cocrystal's powder was directly put on the $BaSO_4$ substrate, thus presenting an absorption spectrum of 300-800 nm and a slit width of 20 nm, which was different compared with the single components and these three Cocrystals.

To further study the PL properties of cocrystals, the emission spectra were obtained on an FL-7000 fluorescence spectrophotometer, and fluorescence micrographs were obtained using a Leica DM2700M optical microscope (300-650 nm) with a plug-in fluorescence unit.

These three solid-state cocrystals were subjected to TGA utilising the TG 209 F3 Tarsus instrument, which is made in Germany by NETZSCH. Under nitrogen gas with cocrystal release dt1.0 and 30-800 °C K/r synchronisation, the TGA was performed. The temperature was set at 10 °C / minute. We also used the DSC technique to observe the melting points of the cocrystals. For this, we used the Polyma instrument manufactured by NETZSCH in Germany and identified single sharp peaks due to melting. The FTIR spectra were obtained using a Bruker Vertex 70 FTIR spectrometer to provide further characterisation. Then, the solid-state cocrystals samples were analyzed using FTIR equipment while nitrogen gas was present. Data were captured by the device between 600 cm^{-1} to 4000 cm^{-1}.

3. Results and Discussions

3.1. Cocrystal Preparation and Its Structure Analysis

Three new organic cocrystals—AETC (CCDC: 2287450), DTTC (CCDC: 2287435), and 3-ATC (CCDC: 2347457)—exhibiting distinct colour emissions and acid-responsive behaviour were designed and prepared. Acenaphthylene (AE), dithieno [3,2-b:2′,3′-d] thiophene (DTT), and 3-aminopyridine (3-AP) were used as electron donors, while tetracyanobenzene (TCNB) served as the electron acceptor. These cocrystals were obtained by slow evaporation of different solutions at room temperature while maintaining the same donor-to-acceptor (D/A) molar ratio. AETC emitted a yellow colour, DTTC an orange colour, and 3-ATC a red colour, different from the colours of their constituents, in that order. According to Figure 1. An extensively performed characterisation technique is X-ray diffraction (XRD), which gives information regarding the crystalline nature and lattice parameters of the material. The PXRD patterns in Figure 2a and S1a display that cocrystals have different peaks from the co-former, indicating successful cocrystallisation instead of the simple sample mixing between different compounds. The measured PXRD result of those cocrystals was consistent with the data calculated through the CIF file.

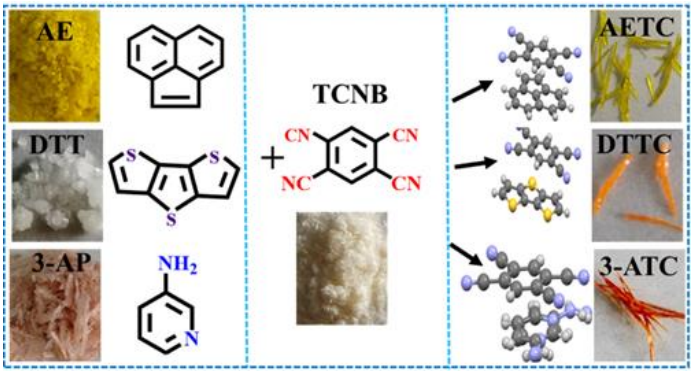


Figure 1: *The images and crystal with the molecular structures of AETC, DTTC, 3-ATC, TCNB, 3-AP and AE powder.*

The superstructures of the cocrystals were determined by single-crystal X-ray diffraction analysis. Among the three cocrystals, AETC and DTTC crystallise in the triclinic system, whereas 3-ATC crystallises in the monoclinic crystal system. However, all structures are assigned to the space groups P-1 and C2/c and exhibit a gradual expansion of their lattice parameters: AETC a = 6.73 Å, b = 8.05 Å, c = 15.24 Å, α = 94.33°, β = 99.82°, γ = 97.76 °; DTTC a = 7.22 Å, b = 9.13 Å, c = 12.66 Å, α = 88.45°, β = 94.84°, γ = 95.12°; and 3-ATC a = 7. 24 Å, b = 15.47 Å, c = 11.65 Å, α = 90°, β = 92.67°, γ= 90°. Additional information is provided in Table S1. As seen in Figure 2b-d, the cocrystals' donor and acceptor molecules are stacked face-to-face, displaying a mixed stacking structure. Furthermore, these three cocrystals exhibit short intermolecular donor–acceptor (D–A) contacts, with distances of 3.35 Å for AETC, 3.47 Å for DTTC, and 3.35 Å for 3-ATC. These short contacts suggest that the cocrystals may possess charge-transfer (CT) character. Additionally, the π–π stacking distances between adjacent molecules in the cocrystals are noteworthy. Thus, as can be seen in Fig. S1b-d, for the AETC cocrystal, the N···H–C distances between adjacent donor–acceptor (D–A) molecules within the column are 3.22 and 3.42 Å, while the acceptor–acceptor (A–A) separation is 5.86 Å. Similarly, in the DTTC cocrystal, the N···H–C distances between neighbouring columnar D–A molecules are 2.56 and 3.34 Å, and the A–A distance is 4.33 Å. For the 3-ATC cocrystal, the corresponding N···H–C distances are 3.12 and 3.21 Å, with an A–A separation of 3.33 Å. These intermolecular interactions contribute to the stabilisation of the three cocrystal structures. Depending on the supramolecular interactions operating along the D–A stacking direction and the C–H···N direction, the cocrystals form one- or two-dimensional low-dimensional organic architectures.

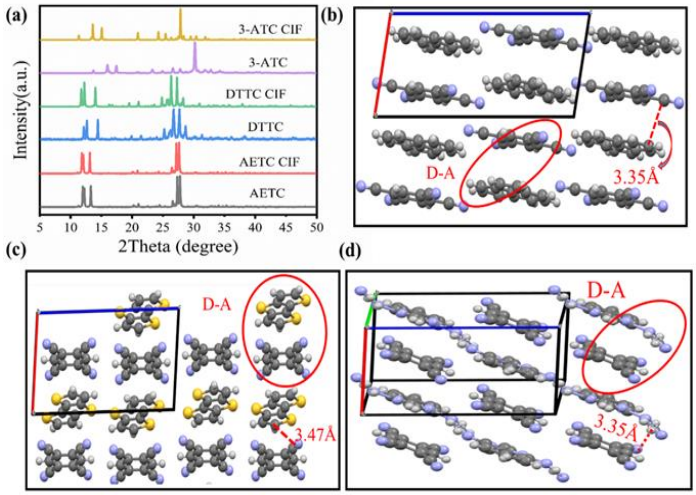


Figure 2: *(a) PXRD, (b, c, d) Crystal structures of AETC, DTTC, 3-ATC.*

Moreover, morphological analysis was conducted using optical microscopy (OM) techniques, which suggested a 1D structure for DTTC, 3-ATC cocrystals, and a 2D structure for AETC cocrystals. The OM results explain the centre and edge images of the silicon wafer slide or sample containing these cocrystals, demonstrating their excellent morphology and quality, as shown in Figure S2a-c. Conversely, the D-As are responsible for the donor-acceptor π-π interaction in the AETC, DTTC, and 3-ATC co-crystals as well as the C−H···N strong hydrogen bonds. These three co-crystals' low-dimensional (1D, 2D) morphology results from the comparison of the C−H···N hydrogen bonds to the donor-acceptor π-π interactions along the mixed donor-acceptor stacking direction.

The molecular orbital energy levels of the AETC, DTTC, and 3-ATC cocrystals were calculated using density functional theory (DFT). The results show that the electron density in the HOMO of all three cocrystals is primarily localised on the donor molecules (AE, DTT, and 3-AP). The HOMO energy levels of AETC, DTTC,

and 3-ATC are −6.66 eV, −6.38 eV, and −6.80 eV, respectively, which are close to those of the corresponding pristine donor molecules (−6.05 eV, −5.89 eV, and −6.01 eV). In contrast, the LUMO is mainly distributed over the acceptor molecule (TCNB), with energy levels of −3.678 eV, −3.67 eV, and −4.67 eV for AETC, DTTC, and 3-ATC, respectively, which are comparable to the LUMO energy level of pristine TCNB (−4.06 eV) (Figure 3a and Figure S3). Based on the molecular orbital distributions, the calculated band gaps of DTTC, AETC, and 3-ATC are 2.98 eV, 2.71 eV, and 2.13 eV, respectively. These values are significantly narrower than those of the individual components. Notably, 3-ATC exhibits the smallest band gap among the three cocrystals (Figure S4). The theoretical simulations indicate that the band gap narrowing originates from the charge-transfer (CT) transition between the donor and acceptor molecules. This result is consistent with the observed absorption behaviour, where the cocrystals display different colours (yellow, orange, and red-shifted), corresponding to their progressively reduced band gaps.

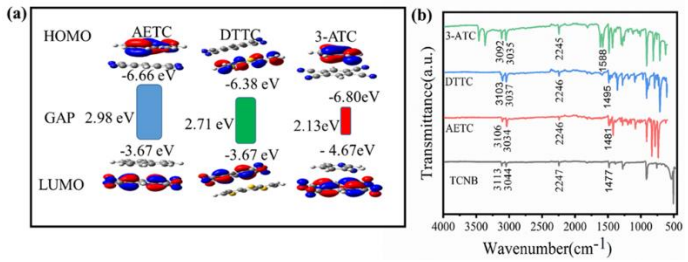


Figure 3: *(a) HOMO and LUMO gap, (b) FTIR of AETC, DTTC, and 3-ATC cocrystals.*

Furthermore, Fourier transform infrared spectra (FTIR) spectroscopy was utilised to expose the minute changes in the molecular environment, to gain a deeper understanding of the charge transfer interactions in these three cocrystals. As Fig. 3b illustrates, when compared to the donors, the crystal's broad absorption spectrum, 600 cm^{-1}-4000 cm^{-1} is remarkable, and the acceptor demonstrated a robust charge transfer connection with the donors. Additionally, the infrared vibration peaks of the cocrystal almost overlap with those of the pristine components, which demonstrates the successful coassembly. The C–H bond stretching vibration peaks of the acceptor TCNB in the cocrystals red-shift and the C≡N bond stretching vibration peak blue-shifts; the sharp peaks of cocrystals suggest that these three cocrystals have excellent crystal quality. The shift of the cocrystals' peak can be attributed to the various interactions between molecules in the cocrystals. For example, in AETC the TCNB 3113 cm^{-1} band (C–H) is shifted to 3106 cm^{-1},3044 cm^{-1} (C–H) is shifted to 3034 cm^{-1}, 2247 cm^{-1}(C≡N) is shifted to 2246 cm^{-1}, in DTTC the TCNB 3113 cm^{-1} band (C─H) is shifted to 3103 cm^{-1},3044 cm^{-1} (C–H) is shifted to 3037 cm^{-1}, 2247 cm^{-1}(C≡N) is shifted to 2246 cm^{-1}, and in 3-ATC the TCNB 3113 cm^{-1} band (C–H) is shifted to 3092 cm^{-1},3044 cm^{-1} (C–H) is shifted to 3035 cm^{-1}, 2247 cm^{-1}(C≡N) is shifted to 2245 cm^{-1}, the peaks observed in this analysis exhibit varying levels of redshift, indicating a rise in electron cloud density on the benzene ring of the TCNB molecule. These electrons between the D and A molecules reveal the CT characteristic in the cocrystals.

3.2. Optical Properties

To get a comprehensive knowledge of the correlation between molecular interactions and photophysical characteristics, we perform in-depth spectroscopic investigations of solid-state crystalline materials. For a complete understanding, various spectra were recorded. Obviously, absorption spectra can be used to distinguish intermolecular interactions. However, the self-assembled three cocrystals show different absorption spectra in the ultraviolet and visible regions with yellow, orange and red shifts of 400 nm, 450 nm and 550 nm, respectively, Figure 4a. These different shifts of the cocrystals in the visible region are due to intermolecular CT from donor to acceptor. Furthermore, DFT calculations of the donor and acceptor molecules indicate that the intermolecular interactions in the cocrystals allow electron delocalisation between the D and A molecules, revealing the CT characteristic in the cocrystals. To further investigate the photoluminescence (PL) properties of the cocrystals, we have measured their PL spectra. The prompt PL spectra exhibit fluorescence emission peaks of AETC, DTTC and 3-ATC located at 500nm, 550nm and 650nm, which exhibit yellow, orange and red colours. As shown in Figure 4b, all these were in the room temperature phosphorescence (RTP) emission and in the solid state of the cocrystals. And different shifts compared to their parents, indicating a small energy gap in the mix-aggregation of the cocrystals, the absorption and emission spectra of the cocrystals based co-forms. In addition, the 2D morphology of the cocrystals increases the specific surface area compared to the 1D structures, which also favours efficient light absorption, strong charge transfer interaction leading to NIR absorption, which is why these three cocrystals show different colours, which are made from different donors with the same acceptor CT and π-π interactions.

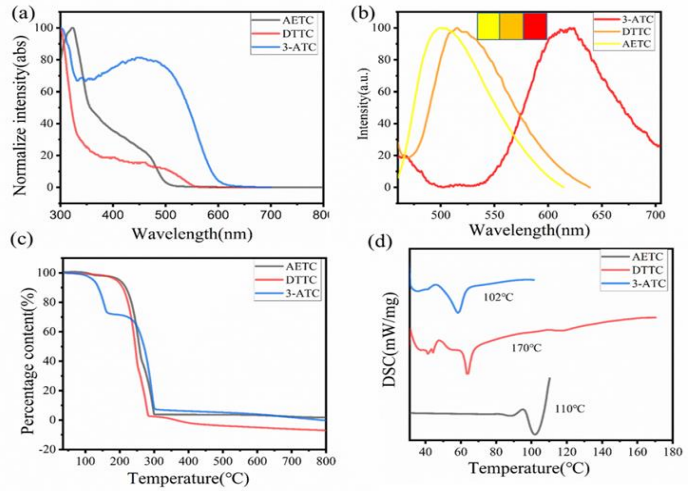


Figure 4: *(a) The absorption, (b) fluorescence, (c) TGA, (d) DSC spectra of AETC, DTTTC and 3-ATC in solid-state.*

Thermo-gravimetric analysis and differential scanning calorimetry (TGA-DSC) measurements reveal that the thermal behaviours of these cocrystals are much alike. Having a very similar temperature for every endothermic process (Figure 4c). Their weights are almost constant at 6.9 mg, 8.3mg and 5.07mg, which indicates that the cocrystals are highly stable under the ambient atmosphere and ensure their practical application. Therefore, the stacking mode and relative orientation of the three cocrystals alternated obviously, which would further influence their RTP emission. Those cocrystals (AETC, DTTC and 3-ATC) have decomposition temperatures of 290℃, 280℃, and 200℃. In general, the sublimation temperature of the single component in cocrystals is higher than that of their single crystals, which indicates that the interactions between molecules in the cocrystals are stronger than those in a single-component crystal. The DSC diagram demonstrates that the melting points of those cocrystals are good, which DSC clear diagram shown in Figure 4d. The melting points of these three AETC, DTTC and 3-ATC cocrystals are 110 ℃, 170 ℃ and 102 ℃, respectively, meaning the cocrystals have a

new crystal lattice, and the high melting point indicates that these cocrystals have a stable structure.

4. Comparing Cocrystals Protonated through Acidic Stimulation

Binary molecular stacking structures in organic CT complexes can be classified as either mixed or separated stacks. Most in-depth investigations so far have been focused on the former cases due to their unconventional metallic (super) conductivities [24]. Recently, mixed-stack donor–acceptor (D–A) charge-transfer (CT) complexes have been reexamined both theoretically and experimentally because of their promising ferroelectric properties [25]. The offsets of D and A frontier molecular orbitals (FMOs) and their unique molecular arrangement primarily determine the electronic characteristics of the CT structures. Therefore, to develop an effective CT cocrystal system, careful selection of the D/A pair with appropriate FMOs is required.

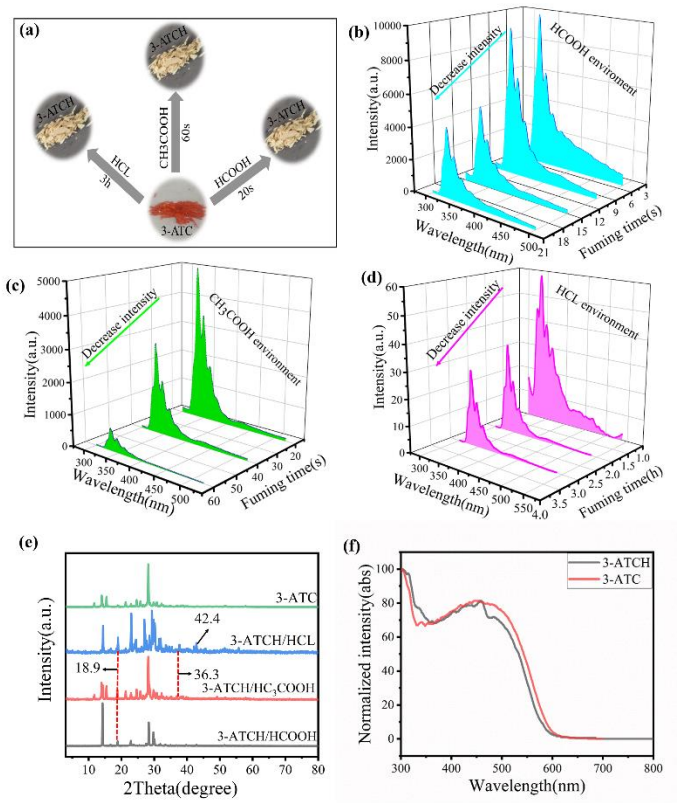


Figure 5: *(a) Images of 3-ATC and 3-ATCH, (b-d) decreased intensities of fluorescence of 3-ATCH, (e) PXRD of 3-ATC and 3-ATCH and (f) UV-vis absorption spectra of 3-ATC and 3-ATCH.*

Anyhow, the AE, a polycyclic aromatic hydrocarbon, is an ortho and peri-fused tricyclic hydrocarbon. The molecule resembles naphthalene with positions 1 and 8 connected by a -CH=CH- unit. It is a yellow solid. And the DTT is a conductive material that acts as a donor building block for synthesising a variety of optoelectronic materials. Additionally, the 3-AP, a weak alkaline compound with a 3-amide group and an N atom on the pyridine ring, can readily form pyridinium salts by interacting with protons. However, we employed three different donor molecules with a common acceptor (TCNB) to design organic cocrystals exhibiting acid-stimulated behaviour. The AE- and DTT-based cocrystals are highly stable under various acid stimuli, likely due to the intrinsic structural characteristics of AE and DTT. In contrast, the 3-AP-based cocrystal shows significantly higher responsiveness to acid stimuli. This study shows that the monomer of the 3-AP-based cocrystal changes colour from red to cream-white when it is protonated through acidic stimulation. Thus, the stimuli-responsive luminescent behaviours of the solid-state 3-ATC were explored during protonation. As shown in Figure 5a, the fluorescence colour of the treated 3-ATC samples (called 3-ATCH) changes from red to cream-white, and the luminescence intensity gradually decreases with time and varies in sensitivity with different acids (Figure S5a-c). During the experiment, the samples were exposed to HCOOH, CH_3COOH, and HCl vapour for different durations ranging from 5 s to 20 s, 60 s, and 3h. The sensitivity of 3-ATC to formic acid was the highest, with a shorter colour change time of 5 seconds. After exposure to alkaline (NH_3) vapour, the fumed ATCH reversibly restores its red emission (Figure S6). The responsive time of 3-ATC is faster than that of most previously reported cocrystals, as shown in Figure 5b-d. To understand this phenomenon, the PXRD patterns of 3-ATC and 3-ATCH were also examined. The PXRD pattern of 3-ATCH shows clear and strong peaks at 18.9°, 36.3° and 42.4°, in contrast to some of the peaks seen in 3-ATC (Figure 5e). It has been shown that the addition of acids during fuming changes the crystal structure of 3-ATC. The 3-ATCH material is a new and unique material with excellent crystallinity. These results suggest that the original 3-ATC and the modified material are combined to form the 3-ATCH sample. CT interactions cause a blue shift in the 3-ATCH absorption region, almost at 500 nm. Due to the electron cloud rearrangement caused by the addition of electron-withdrawing H+ during the smelting process, the band gap of 3-ATCH widens compared to 3-ATC and the D-A interactions become weaker (Figure 5f).

5. Conclusion

In summary, the new organic cocrystals of different donors (AE, DTT and 3-Ap) with the same acceptor (TCNB) have been obtained by molecular self-assembly. The complementary electrostatic potential energy of donor and acceptor molecules makes the cocrystals have excellent CT interactions. FTIR spectra, UV–vis absorption spectra, fluorescence spectra, DFT, OM and X-ray diffraction show significant differences in stabilities and photophysical behaviours between cocrystals and single components. As a result, among these cocrystals, 3-ATC exhibits the highest sensitivity to various acid stimuli, with fluorescence switching occurring within seconds. In contrast, the other two cocrystals, AETC and DTTC, are sufficiently robust to resist acid-induced changes. This study provides some suggestions for the preparation of multifunctional organic low- dimensional cocrystals (1D, 2D), and smart materials.

Declaration

Acknowledgment: The authors gratefully acknowledge the financial support from the National Key R&D Program (2022YFA1204401), the Tianjin Natural Science Foundation (20JCJQJC00300), and the Fundamental Research Funds for the Central Universities.

AI Disclosure: N/A

Author Contribution Statement: D. K. Hassand performed the material preparation and characterisation; N. A. Zahedi, A. S. Hamid and M. Sharif conducted the theoretical calculations; all authors contributed to discussions and manuscript review.

Availability of Data and Materials: Data will be made available by the corresponding author on reasonable request.

Competing Interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Consent to Publish: The authors agree to publish the version of the manuscript in this journal.

Ethical Issues: There are no ethical issues.

Funding Statement: This work was financially supported by the National Key R&D Program (2022YFA1204401), Tianjin Natural Science Foundation (20JCJQJC00300), and the Fundamental Research Funds for the Central Universities.

References

1. S. Sato, H. Nikawa, S. Seki, L. Wang, G. Luo, J. Lu, M. Haranaka, T. Tsuchiya, S. Nagase, T. Akasaka, Angew. Chemie - Int. Ed. (2012), 51, 1589–1591.
2. T. Wakahara, P. D'Angelo, K. Miyazawa, Y. Nemoto, O. Ito, N. Tanigaki, D.D.C. Bradley, T.D. Anthop ou los, J. Am. Chem. Soc. (2012), 134, 7204–7206.
3. N. Schultheiss, A. Newman, , Cryst. Growth &Design. (2009), 9, 2950–2967.
4. J. Zhang, H. Geng, T.S. Virk, Y. Zhao, J. Tan, C.A. Di, W. Xu, K. Singh, W. Hu, Z. Shuai, Y. Liu, D. Zhu, Adv. Mater. (2012), 24, 2603–2607.
5. H. Dong, H. Zhu, Q. Meng, X. Gong, W. Hu, Chem. Soc. Rev. (2012), 41, 1754–1808.
6. S.K. Park, J.H. Kim, T. Ohto, R. Yamada, A.O.F. Jones, D.R. Whang, I. Cho, S. Oh, S.H. Hong, J.E. Kwon, J.H. Kim, Y. Olivier, R. Fischer, R. Resel, J. Gierschner, H. Tada, S.Y. Park, Adv. Mater. (2017), 29, 201701346.
7. B. Zhou, Q. Zhao, L. Tang, D. Yan, Chem. Commun. (2020), 56, 7698–7701.
8. L. Sun, W. Zhu, W. Wang, F. Yang, C. Zhang, S. Wang, X. Zhang, R. Li, H. Dong, W. Hu, Angew. Chemie - Int. Ed. (2017), 56, 7831–7835.
9. M. Jiang, S. Li, C. Zhen, L. Wang, F. Li, Y. Zhang, W. Dong, X. Zhang, W. Hu, Front. Optoelectron. (2022), 15, 1–10.
10. J. Jin, S. Wu, Y. Ma, C. Dong, W. Wang, X. Liu, H. Xu, G. Long, M. Zhang, J. Zhang, W. Huang, ACS Appl. Mater. Interfaces. (2020), 12, 19718–19726.
11. Y.L. Lei, Y. Jin, D.Y. Zhou, W. Gu, X.B. Shi, L.S. Liao, S.T. Lee, Adv. Mater. (2012), 24, 5345–5351.
12. D. Khan, M.A.B.A , Zhang Xiaotao, Muhammad Hasnain Jameel, uhammad S.B.R. and M.A. MBajaber, Micro Nano Syst. Lett. (2023), 11:24, 2- 9.
13. S. Li, D. Yan, ACS Appl. Mater. Interfaces. (2018), 10, 22703–22710.
14. H. Jiang, C. Kloc, MRS Bull. (2013), 38, 28–33.
15. D. Braga, L. Maini, F. Grepioni, Chem. Soc. Rev. (2013), 42, 7638–7648.
16. M. Jiang, C. Zhen, S. Li, X. Zhang, W. Hu, Front. Chem. (2021), 9, 1–16.
17. H. wenping zhu weigang, zhen yonggang, Dong huanli, Fu hongbing, Prog. Chem. (2014), 26, 1292–1306.
18. Y.L. Lei, L.S. Liao, S.T. Lee, J. Am. Chem. Soc. (2013), 135, 3744–3747.
19. Y. Liu, Q. Zeng, B. Zou, Y. Liu, B. Xu, W. Tian, Angew. Chemie - Int. Ed. (2018), 57, 15670–15674.
20. L. Sun, W. Zhu, F. Yang, B. Li, X. Ren, X. Zhang, W. Hu, Phys. Chem. Chem. Phys. (2018), 20, 6009–6023.
21. L. Sun, Y. Wang, F. Yang, X. Zhang, W. Hu, Adv. Mater. (2019), 31, 1–22.
22. Y. Liu, A. Li, S. Xu, W. Xu, Y. Liu, W. Tian, B. Xu, Angew. Chemie - Int. Ed. (2020), 59, 15098–15103.
23. W. Hu, H. Zhang, K. Salaita, H. Sirringhaus, SmartMat. (2020), 1, 1014.
24. D. Jérome, A. Mazaud, M. Ribault, K. Bechgaard, D. Jérome, A. Mazaud, M. Ribault, K. Bechgaard, HAL. (2008), 23, 1730.
25. Y. Zhai, S. Li, J. Li, S. Liu, T.D. James, J.L. Sessler, Z. Chen, Nat. Commun. (2023), 14, 1–10.

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Journal of Engineering, Science and Technological Trends (JESTT)

Vol. 3, Issue 2, July 2026
DOI: https://doi.org/10.64060/JESTT3i22

Article

Neutrosophic Modelling of Qubit Uncertainty in Noisy Quantum Computing Systems

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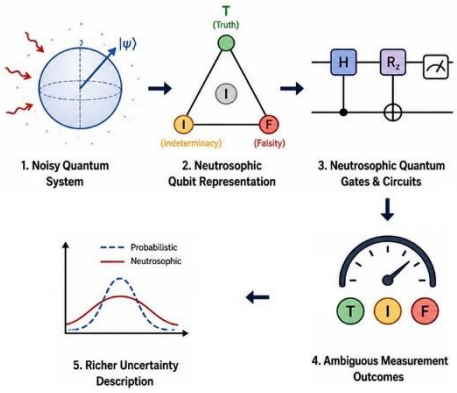
Received: 16 March 2026 / Revised: 28 April 2026 / Accepted: 05 May 2026 / Published online: 11 May 2026

ABSTRACT

Quantum computing exploits superposition and entanglement to perform computations beyond the capabilities of classical machines. However, practical quantum systems operate under substantial environmental noise, measurement uncertainty, and decoherence, leading to ambiguous or partially determined quantum states. Conventional probabilistic descriptions capture stochastic behaviour but do not explicitly represent indeterminacy arising from incomplete information or measurement ambiguity. In this work, we introduce a neutrosophic representation of qubit states that integrates principles of Neutrosophic Logic with the mathematical framework of Quantum Computing. In the proposed model, a qubit is characterised by three independent parameters representing truth, indeterminacy, and falsity. This formulation enables explicit representation of ambiguous quantum states and uncertain measurement outcomes. We extend the neutrosophic formalism to quantum gate operations and analyse how the model captures uncertainty propagation in quantum circuits. Through theoretical examples and graphical analysis, we demonstrate that neutrosophic representation provides a richer description of uncertainty compared with conventional probabilistic approaches. The proposed framework offers a conceptual pathway for improved modelling of noisy intermediate-scale quantum devices and may contribute to the development of uncertainty-aware quantum computing architectures.



Keywords: Ambiguous Quantum States; Neutrosophic Logic; Noisy Quantum Systems; Quantum Circuits; Quantum Computing; Uncertainty Modelling

1. Introduction

The rapid development of quantum technologies has led to increasing interest in quantum computation as a transformative approach to information processing [1],[2],[3],[4]. Unlike classical computers, which process information using deterministic binary bits, quantum computers operate using quantum bits or qubits that obey the laws of quantum physics [5]. Because qubits can exist simultaneously in multiple states, quantum computers can explore a vast computational space through quantum parallelism. The fundamental theoretical framework underlying quantum computation is derived from Quantum Mechanics, which describes the behaviour of physical systems at microscopic scales [6],[7]. Quantum systems exhibit several counterintuitive properties that are central to quantum information processing. Among these properties, superposition allows a qubit to exist in a linear combination of basis states, while entanglement enables strong correlations between multiple qubits.

Despite these advantages, practical quantum computing faces formidable challenges. Quantum systems are extremely sensitive to external disturbances, and interactions with the surrounding environment can quickly destroy the coherence of quantum states [8],[9],[10],[11]. This process, known as Quantum Decoherence, represents one of the major obstacles to the realisation of large-

scale quantum computers. Even small amounts of noise can accumulate during quantum computations, leading to errors that significantly degrade algorithmic performance. Conventional approaches to modelling quantum uncertainty rely on probabilistic descriptions [12]. In the standard quantum formalism, the outcome of a measurement is described by a probability distribution derived from the square magnitudes of probability amplitudes. While this probabilistic representation successfully captures the stochastic nature of quantum measurements, it does not always distinguish between randomness and ambiguity. In many practical situations, uncertainty arises not only from intrinsic probabilistic behaviour but also from incomplete knowledge of system parameters or limitations of measurement devices.

To address this issue, alternative frameworks capable of representing indeterminacy explicitly have been explored. One such framework is Neutrosophic Logic, which was introduced by Florentin Smarandache as a generalisation of classical and fuzzy logic [13],[14]. Neutrosophic logic represents information using three independent components: truth, indeterminacy, and falsity. Unlike probabilistic approaches, which constrain the sum of probabilities to unity, neutrosophic logic allows these components to vary independently, enabling a more flexible representation of uncertain information.

The objective of this work is to explore the potential of neutrosophic theory as a framework for modelling uncertainty in quantum computing systems. By extending the conventional description of qubit states to include indeterminacy, we aim to provide a richer representation of the uncertainties encountered in realistic quantum hardware. In particular, we focus on noisy quantum computing platforms where measurement errors, gate imperfections, and environmental disturbances introduce ambiguity into quantum operations.

2. Conventional Quantum State Representation

2.1. Mathematical Description of Qubits

In quantum computing, the fundamental unit of information is the quantum bit, or qubit. Unlike a classical bit, which can exist only in one of two definite states, 0 or 1, a qubit can exist in a superposition of these basis states. Mathematically, a single qubit can be represented as a vector in a two-dimensional complex Hilbert space, expressed as in (1) [15],[16],[17]:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \quad (1)$$

Here, $|0\rangle$ and $|1\rangle$ denote the computational basis states of the qubit, and $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ are complex probability amplitudes. These amplitudes encode the quantum information of the system and determine the probability distribution of measurement outcomes [18]. Importantly, the normalisation condition must be satisfied as in (2):

$$|\alpha|^2 + |\beta|^2 = 1 \quad (2)$$

This ensures that the total probability of measuring the qubit in one of the two possible states is unity, consistent with the axioms of probability theory. The squared magnitudes of the amplitudes, $|\boldsymbol{\alpha}|^2$ and $|\boldsymbol{\beta}|^2$, represent the probabilities of finding the qubit in state $|0\rangle$ or $|1\rangle$, respectively, upon measurement.

The probabilistic nature of quantum measurement is a fundamental feature of quantum mechanics. When a measurement is performed, the qubit's wavefunction collapses into one of the basis states, a process dictated by the Born rule [19],[20]. This collapse is inherently stochastic: repeated measurements of identically prepared qubits will yield outcomes consistent with the probabilities $|\boldsymbol{\alpha}|^2$ and $|\boldsymbol{\beta}|^2$, but individual results cannot be predicted deterministically. This probabilistic behaviour is central to quantum theory and underpins phenomena such as quantum interference, entanglement, and nonlocal correlations. Qubits can be manipulated through unitary operations, represented by 2×2 matrices acting on the state vector [21]. These operations allow rotations on the Bloch sphere, enabling the creation of arbitrary superpositions [22]. For instance, the Hadamard gate, a single-qubit unitary operation, transforms a qubit from a basis state into an equal superposition of $|0\rangle$ and $|1\rangle$ [23],[24]. Such transformations are the foundation of quantum algorithms, allowing the construction of complex computational processes through sequences of unitary operations.

The mathematical representation of qubits is compact yet highly expressive. In addition to single-qubit states, multi-qubit systems are described by tensor products of individual qubits. For example, a two-qubit system may exist in a linear combination of the four basis states $|00\rangle$, $|01\rangle$, $|10\rangle$, $|11\rangle$, with complex amplitudes assigned to each [25],[26]. These higher-dimensional Hilbert spaces enable entanglement, a uniquely quantum correlation with no classical analog, which forms the basis of many quantum computing advantages, including quantum teleportation and superdense coding.

2.2. Limitations of Probabilistic Descriptions

While probabilistic descriptions form the foundation of quantum mechanics, they are often insufficient to capture the full spectrum of uncertainties in practical quantum computing systems. Real-world quantum devices, including superconducting qubits, trapped ions, and photonic systems, experience environmental and operational imperfections that introduce additional layers of uncertainty beyond ideal probabilistic behaviour [27],[28],[29],[30],[31].

- A primary source of such uncertainty is environmental noise, arising from interactions between qubits and their surroundings. Thermal fluctuations, electromagnetic interference, and residual couplings can perturb qubit states, leading to deviations from ideal evolution. These effects contribute not only to stochastic errors but also to ambiguity, as qubits may occupy partially decohered states where outcome probabilities are not sharply defined.
- Imperfect control pulses further exacerbate uncertainty. Quantum gates rely on precisely tuned electromagnetic or optical pulses; small deviations in amplitude, duration, or phase can cause unintended rotations. While some errors are statistical, others produce indeterminate states that do not align neatly with standard probabilistic distributions. Calibration errors, affecting qubit frequencies, coupling strengths, or timing, introduce systematic biases that can distort evolution and generate outcomes that remain uncertain despite being deterministic.
- Finally, measurement ambiguity limits the extraction of reliable information. Noise in readout devices, overlapping signal distributions, or finite resolution can produce results that are intrinsically indeterminate. For instance, in dispersive readout of superconducting qubits, intermediate voltage signals may prevent unambiguous assignment to $|0\rangle$ or $|1\rangle$. Conventional probabilistic models interpret this as a weighted average but fail to capture the qualitative indeterminacy of such outcomes.

Collectively, these considerations highlight the need for frameworks that explicitly account for both stochastic and indeterminate uncertainties, enabling more accurate modelling and robust design of quantum systems.

Despite the effectiveness of probabilistic and density-matrix-based models, existing frameworks do not explicitly distinguish between intrinsic quantum randomness and uncertainty arising from ambiguity or incomplete information. In practical quantum

systems, measurement outcomes may be indeterminate rather than purely probabilistic, particularly under conditions of noise, partial decoherence, or limited readout resolution. Conventional metrics such as fidelity or error rates aggregate these effects into a single value, thereby obscuring their physical origin. This limitation motivates the need for an extended framework capable of explicitly representing and separating stochastic, indeterminate, and erroneous contributions to quantum uncertainty.

3. Neutrosophic Representation of Qubit States

3.1. Neutrosophic Logical Framework

In classical and quantum information theory, uncertainty is traditionally represented using probabilities. However, probabilistic models primarily capture stochastic randomness and often fail to explicitly represent indeterminacy arising from incomplete knowledge or ambiguous measurement outcomes. To address this limitation, neutrosophic logic offers a generalised framework capable of representing both randomness and indeterminacy.

Neutrosophic logic, introduced by Florentin Smarandache, extends the principles of fuzzy logic by incorporating three independent components to characterise any statement or system state [14],[32]. A neutrosophic entity is defined as a triplet (3):

$$N = (T, I, F) \quad (3)$$

Where:

- $\boldsymbol{T}$ represents the degree of truth, quantifying the extent to which a proposition is verified or confirmed.
- $\boldsymbol{I}$ represents the degree of indeterminacy, reflecting uncertainty, ambiguity, or incomplete knowledge.
- $\boldsymbol{F}$ represents the degree of falsity, capturing contradictory or erroneous information.

Unlike conventional probabilities, these components are independent; they are not required to sum to unity. Each can vary freely within a defined range, allowing the representation of conflicting, incomplete, or ambiguous information. This flexibility is particularly relevant for modelling real-world quantum systems, where noise, decoherence, and measurement imperfections create states that cannot be fully described by standard probabilistic amplitudes alone.

The neutrosophic framework is versatile and can represent classical deterministic states (where $\boldsymbol{T} = 1$, $\boldsymbol{I} = 0$, $\boldsymbol{F} = 0$), fully indeterminate states (where I dominates), or conflicting information (where $\boldsymbol{T}$ and $\boldsymbol{F}$ are both significant). It thus provides a richer language for describing uncertainty in both theoretical and experimental contexts.

It is important to emphasise that the proposed neutrosophic representation is not intended to replace the standard formalism of quantum mechanics, but rather to complement it as an additional uncertainty modelling layer. The triplet ($\boldsymbol{T}$, $\boldsymbol{I}$, $\boldsymbol{F}$) can be interpreted as a phenomenological abstraction derived from measurement statistics associated with quantum states described in Hilbert space. In this context, the component $\boldsymbol{T}$ is consistent with probabilities obtained via the Born rule, while $\boldsymbol{I}$ capture indeterminacy arising from measurement ambiguity, noise, and incomplete information and $\boldsymbol{F}$ reflects erroneous or contradictory outcomes due to imperfections in quantum operations or readout. Similarly, the framework is compatible with density matrix descriptions and completely positive trace-preserving (CPTP) maps, in the sense that neutrosophic parameters can be viewed as higher-level descriptors derived from the action of noisy quantum channels on measurement outcomes. Thus, the proposed model should be understood as an extension that augments, rather than modifies, the underlying quantum mechanical structure.

3.2. Definition of a Neutrosophic Qubit

Building on this framework, we define a Neutrosophic Qubit (NQ) as a quantum state augmented with explicit measures of indeterminacy and falsity. Formally, a neutrosophic qubit is represented as (4):

$$NQ = (T, I, F) \quad (4)$$

Where:

- $\boldsymbol{T}$ corresponds to the confirmed probability of a quantum state, analogous to the conventional amplitude-derived probability in standard quantum mechanics.
- $\boldsymbol{I}$ quantify indeterminacy arising from noise, decoherence, measurement ambiguity, or incomplete knowledge of the system.
- $\boldsymbol{F}$ represents contradictory or erroneous information, such as outcomes inconsistent with the prepared state due to errors in gate operations or readout devices.

Unlike traditional quantum states, which are normalised by the sum of squared amplitudes, the neutrosophic qubit obeys a relaxed condition (5):

$$0 \leq T + I + F \leq 30 \quad (5)$$

This allows the three components to vary independently, reflecting the realistic scenario where some portion of uncertainty may be ambiguous rather than purely stochastic. In this way, the neutrosophic qubit provides a multi-dimensional characterisation of uncertainty, separating deterministic, random, and indeterminate contributions.

The constraint $0 \leq \boldsymbol{T}, \boldsymbol{I}, \boldsymbol{F} \leq 1$ with $0 \leq \boldsymbol{T} + \boldsymbol{I} + \boldsymbol{F} \leq 3$arises naturally from neutrosophic logic, where each component represents an independent degree of truth, indeterminacy, and falsity. Unlike probabilistic representations, these components are not required to sum to unity. This independence allows the framework to model incomplete information ($\boldsymbol{T} + \boldsymbol{I} + \boldsymbol{F} < 1$), fully specified but non-exclusive information ($\boldsymbol{T} + \boldsymbol{I} + \boldsymbol{F} = 1$), and conflicting or redundant information ($\boldsymbol{T} + \boldsymbol{I} + \boldsymbol{F} > 1$). In quantum systems, this flexibility is physically meaningful, as measurement outcomes may simultaneously exhibit partial correctness, ambiguity due to decoherence, and error due to noise or miscalibration. Therefore, the relaxed constraint is not arbitrary but reflects the multi-source nature of uncertainty in realistic quantum hardware.

3.3. Example 1: Measurement Under Noise

To illustrate the utility of this representation, consider a qubit prepared in an equal superposition state (6):

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \quad (6)$$

In an idealised measurement scenario, the probabilities of observing $|0\rangle$ or $|1\rangle$ are both 0.5. However, in realistic experimental conditions, measurement devices are subject to noise, finite resolution, and other imperfections. Suppose that upon repeated measurement, the outcomes yield the following characterisation as in Table 1:

Table 1:
Parameters for measurement

Parameter	Value
Truth (correct state identification)	0.48
Indeterminacy (ambiguous outcome)	0.32
Falsity (incorrect identification)	0.20

Here, $\boldsymbol{T} = 0.48$ reflects the fraction of measurements correctly identifying the state. The indeterminacy component $\boldsymbol{I} = 0.32$ accounts for outcomes that cannot be confidently assigned to either basis state due to noise or measurement overlap. Finally, $\boldsymbol{F} =$

0.20 represents erroneous results, arising from misclassification or experimental error. Thus, the neutrosophic qubit can be written as (7):

$$NQ = (0.48, 0.32, 0.20) \quad (7)$$

This representation provides several advantages over conventional probabilistic descriptions. Firstly, it explicitly separates ambiguity from randomness, offering a more accurate depiction of experimental reality. Secondly, it provides a clear metric to evaluate the quality of qubit preparation and measurement: a high indeterminacy component signals that improvements in readout or environmental isolation may be necessary, whereas a high falsity component indicates systematic errors. Lastly, this framework is extensible to multi-qubit systems, allowing the quantification of indeterminacy and error propagation in complex quantum circuits.

- **Interpretation and Significance**

The neutrosophic qubit formalism highlights a key distinction: while classical probabilities capture stochastic uncertainty, they do not adequately describe epistemic uncertainty or ambiguous outcomes. In practice, both types of uncertainty coexist. For example, a qubit in a noisy superconducting circuit may occasionally produce measurements that are neither strictly $|0\rangle$ nor $|1\rangle$, reflecting the combined effects of decoherence, control errors, and detector limitations. Standard probabilistic models would interpret these outcomes as averaged probabilities, masking the qualitative difference between random and indeterminate contributions. The neutrosophic approach preserves this distinction, providing a richer, more informative characterisation.

Furthermore, the framework can inform error mitigation and quantum algorithm design. By quantifying indeterminacy, one can identify operations or gates that contribute disproportionately to ambiguous outcomes, enabling targeted hardware or software corrections. It also facilitates the assessment of measurement strategies: for instance, repeated or ensemble measurements can reduce the indeterminacy component, converting ambiguous information into confirmed probabilities while still accounting for residual errors.

4. Neutrosophic Modelling of Quantum Gates

Quantum computation relies on the precise manipulation of qubits through quantum gates, which perform unitary operations on quantum states [33],[32],[35]. In the idealised framework of quantum mechanics, these gates are deterministic and invertible, transforming qubit states with perfect fidelity. For instance, single-qubit gates such as the Hadamard or Pauli-X gates rotate qubits on the Bloch sphere, while multi-qubit gates such as the Controlled-NOT (CNOT) entangle qubits to enable non-classical correlations [36]. However, in practical implementations, gates are subject to a variety of imperfections, including control errors, environmental disturbances, and decoherence. These imperfections introduce uncertainty in the resulting quantum states, which cannot be fully captured by standard probabilistic descriptions alone.

To address this limitation, we extend the neutrosophic framework to model quantum gate operations. In this approach, a Neutrosophic Gate (NG) is defined as a triplet (8):

$$G_N = (T_g, I_g, F_g) \quad (8)$$

Where:

- ***Tg*** quantifies the degree to which the gate performs its intended operation correctly.
- ***Ig*** represents the indeterminacy arising from factors such as environmental noise, control imprecision, or incomplete knowledge of system parameters.
- ***Fg*** captures errors or contradictory outcomes generated during gate execution.

Unlike conventional fidelity metrics, which typically reduce all uncertainties to a single probability of correct operation, the neutrosophic gate model separates stochastic errors from ambiguous or indeterminate behaviours, providing a more nuanced description of real quantum operations.

4.1. Single-Qubit Gates

Consider a single-qubit gate, such as the Hadamard gate, designed to create an equal superposition from a computational basis state [37]. In a noise-free environment, the transformation of $|0\rangle$ yields (9):

$$|0\rangle \xrightarrow{H} = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \quad (9)$$

In a realistic experimental scenario, however, imperfections in pulse amplitude, duration and phase may prevent the qubit from reaching this ideal superposition. Additionally, interaction with the environment can introduce partial decoherence, leaving the qubit in an intermediate state that is not accurately represented by probabilities alone. Using the neutrosophic framework, we can characterise the gate operation as (10):

$$G_N = (0.92, 0.05, 0.03) \quad (10)$$

Here, $T_g = 0.92$ indicates that the gate correctly produces the desired superposition with 92% certainty, $I_g = 0.05$ quantifies the ambiguous fraction of operations where the qubit state is indeterminate due to noise and $F_g = 0.03$ represents the probability of erroneous outcomes caused by miscalibration or control errors. This decomposition allows experimenters to identify and quantify sources of uncertainty beyond conventional fidelity measures.

4.2. Multi-Qubit Gates

Multi-qubit gates, such as the CNOT gate, are central to entanglement generation and complex quantum algorithms [38], [39]. In practice, these gates are highly sensitive to crosstalk, timing errors, and environmental perturbations. Suppose a two-qubit system is intended to undergo a CNOT operation:

$$|00\rangle \xrightarrow{CNOT} |00\rangle, |01\rangle \xrightarrow{CNOT} |01\rangle, |10\rangle \xrightarrow{CNOT} |11\rangle, |11\rangle \xrightarrow{CNOT} |10\rangle$$

In the presence of noise, the resulting state may deviate from these ideal mappings. Some outcomes may be probabilistically correct, others may result in indeterminate superpositions due to decoherence, and a fraction may be completely erroneous. A neutrosophic characterisation of the CNOT gate might be (11):

$$G_N = (0.87, 0.08, 0.05) \quad (11)$$

This decomposition indicates that 87% of operations yield the intended transformation, 8% result in indeterminate outcomes, and 5% are erroneous. Notably, the indeterminacy component I_g captures the ambiguity introduced by partial entanglement or decoherence, information that standard probabilistic fidelity metrics cannot isolate.

4.3. Propagation of Neutrosophic Uncertainty in Quantum Circuits

One of the key advantages of the neutrosophic framework is its ability to track uncertainty through sequential gate operations. In conventional models, the fidelity of a quantum circuit is typically approximated by the product of individual gate fidelities, assuming purely stochastic errors. However, this approach does not account for the accumulation of indeterminate states, which can significantly impact algorithm performance.

Using the neutrosophic approach, if a circuit consists of sequential gates G_1, G_2, …, G_n, the resulting qubit state can be represented as (12):

$$NQ_{final} = (T_{final}, I_{final}, F_{final}) \quad (12)$$

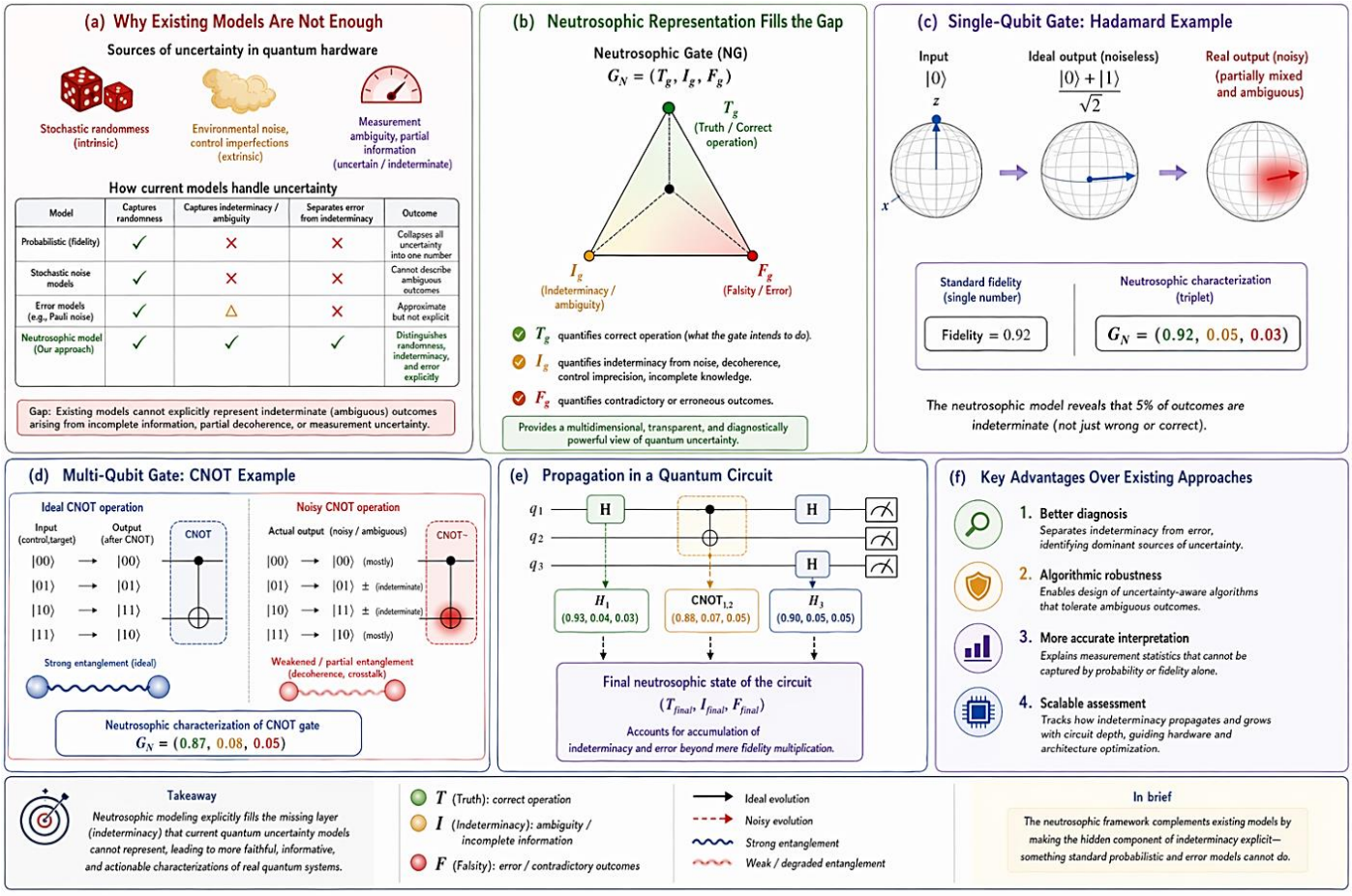


Figure 1: Conceptual illustration of neutrosophic modeling of quantum gates. (a) Comparison between ideal unitary evolution and noisy gate operation. (b) Neutrosophic representation of a quantum gate using the triplet (Tg, Ig, Fg), capturing correct operation, indeterminacy and error. (c) Application to a single-qubit Hadamard gate under realistic noise. (d) Extension to multi-qubit CNOT gate with partial entanglement and decoherence. (e) Propagation of neutrosophic uncertainty in a quantum circuit.

Where each component is updated according to the cumulative effects of gate imperfections, indeterminacy, and errors. For example, if the sequential application of two gates produces:

$G_1 = (0.90, 0.05, 0.05)$, $G_2 = (0.85, 0.10, 0.05)$

Then the resulting neutrosophic state accounts for both propagation of correct operations and accumulation of indeterminacy. Techniques from neutrosophic algebra can be used to combine these triplets systematically, providing a comprehensive model of uncertainty in complex circuits.

4.4. Propagation of Neutrosophic Uncertainty in Quantum Circuits

The neutrosophic representation of quantum gates offers several practical benefits:

- **Error Diagnosis**: By separating correct operation, indeterminacy, and error, experimenters can identify which sources of uncertainty dominate, guiding hardware improvements and control optimisations.
- **Algorithm Robustness**: Quantifying indeterminacy allows algorithm designers to account for ambiguous states, developing error-resilient strategies and redundancy schemes.
- **Measurement Interpretation**: By combining neutrosophic qubits with neutrosophic gates, the model provides a more accurate description of readout statistics, distinguishing between probabilistic and ambiguous outcomes.
- **Scalability Assessment**: As circuits grow in depth, the propagation of indeterminacy can be explicitly quantified, offering insights into the limits of practical quantum hardware and helping optimise circuit architectures.

4.5. Example: Noisy Quantum Circuit

Consider a three-qubit circuit consisting of a Hadamard gate on qubit 1, followed by a CNOT between qubits 1 and 2, and a second Hadamard on qubit 3. Suppose the gates are characterised as:

$H_1 = (0.93, 0.04, 0.03)$, $CNOT_{1,2} = (0.88, 0.07, 0.05)$, $H_3 = (0.90, 0.05, 0.05)$

The neutrosophic formalism allows systematic computation of the final state neutrosophic triplet, capturing how indeterminacy and error propagate through the circuit. The resulting representation can then be compared against experimental measurements to validate hardware performance and refine error mitigation strategies.

5. Discussion

The neutrosophic representation of quantum states and operations presented in this work offers a significant conceptual extension of conventional probabilistic models used in quantum computing, as mentioned in Figure 1. Traditional descriptions of qubits rely primarily on probabilities derived from amplitude magnitudes to characterise stochastic uncertainty. While this approach effectively captures the inherent randomness associated with quantum measurement, it does not fully address situations where uncertainty arises from incomplete information,

measurement ambiguity, or experimental noise. The neutrosophic framework explicitly incorporates a third component, indeterminacy, alongside truth and falsity, enabling a more nuanced and multidimensional description of quantum states.

One of the key advantages of this framework lies in its ability to distinguish between randomness and indeterminacy. In practical quantum hardware, these two forms of uncertainty have distinct origins and implications. Randomness is intrinsic to quantum mechanics and is captured naturally by standard probability theory. Indeterminacy, on the other hand, arises from extrinsic factors such as environmental noise, control imperfections, calibration errors, and limitations of measurement devices. By treating these components separately, the neutrosophic representation provides a richer depiction of quantum states and operations, allowing researchers to identify and quantify the contributions of each source of uncertainty. For example, in superconducting qubits, a portion of observed measurement errors may be due to stochastic processes, while another portion may reflect indeterminate outcomes caused by partial decoherence or finite readout resolution. Conventional probability metrics would aggregate these effects into a single fidelity measure, potentially obscuring the underlying physics.

The framework also provides practical advantages for characterising noisy quantum hardware. Quantifying indeterminacy offers insight into the quality of control and measurement protocols, allowing experimentalists to identify specific operations or hardware components that contribute disproportionately to ambiguous outcomes. This information can be invaluable for targeted hardware improvements, calibration adjustments, and optimisation of gate operations. By explicitly separating falsity from indeterminacy, one can distinguish between systematic errors and ambiguous states, facilitating more precise error diagnostics and performance evaluation.

Furthermore, neutrosophic modelling has significant implications for quantum algorithm design and error mitigation strategies. In conventional error correction, the focus is primarily on stochastic errors. However, when indeterminate states are present, algorithms may fail in ways not predicted by standard probability-based models. Incorporating neutrosophic representations into the design and simulation of quantum circuits allows for uncertainty-aware optimisation, where both ambiguous and erroneous outcomes are considered. Such an approach could improve algorithmic robustness, guide the development of error-resilient circuits, and help allocate resources for measurement repetitions or gate calibration more efficiently.

Another promising avenue is the integration of neutrosophic modelling with quantum information measures. Entropy, mutual information, and coherence metrics are central to understanding quantum systems, but conventional formulations do not explicitly account for indeterminacy arising from incomplete knowledge. Extending these measures within a neutrosophic framework could provide a more comprehensive description of information flow, decoherence, and uncertainty propagation in complex quantum circuits. Similarly, neutrosophic formalism can be incorporated into quantum error correction protocols, enhancing their ability to distinguish between random errors and ambiguous states, potentially improving correction performance in near-term noisy devices.

From a broader perspective, the neutrosophic approach provides a conceptual bridge between theoretical quantum mechanics and experimental realities. It offers a systematic way to quantify uncertainty in systems where noise and partial information play critical roles, which is particularly relevant for noisy intermediate-scale quantum (NISQ) devices. As quantum hardware scales up, the cumulative effects of gate imperfections, decoherence, and readout ambiguity will become increasingly significant. Neutrosophic modelling provides a framework to anticipate and quantify these effects, informing both hardware development and algorithm design.

In brief, the neutrosophic representation enriches the existing quantum computational toolkit by providing a multidimensional, explicit characterisation of uncertainty. It complements standard probabilistic models, offering insights into measurement ambiguity, indeterminate outcomes, and error propagation that are not captured by conventional methods. Future research directions include systematic experimental validation, integration with quantum error correction protocols, extension to multi-qubit and hybrid quantum-classical systems, and development of neutrosophic metrics for quantum information measures. Collectively, these developments may contribute to more reliable, scalable, and uncertainty-aware quantum computation, bridging the gap between idealised theory and the realities of experimental quantum hardware.

6. Conclusion

This study has introduced a neutrosophic representation of quantum states and gates, extending conventional probabilistic models by explicitly incorporating indeterminacy alongside truth and falsity. This framework enables a multidimensional characterisation of uncertainty, distinguishing between stochastic randomness, ambiguous outcomes, and erroneous results. NQ provides a clear description of real-world qubit behaviour, while neutrosophic modelling of quantum gates allows tracking of uncertainty propagation in circuits, informing robust algorithm design and error mitigation strategies. By bridging theoretical quantum models and experimental realities, the framework supports diagnostics, hardware optimisation, and evaluation of noisy intermediate-scale quantum devices. Overall, neutrosophic modelling offers a practical, flexible approach to enhance reliability, scalability, and robustness in quantum computation.

Declaration

AI Disclosure: N/A

Author Contribution Statement: M. R. S. wrote the whole paper.

Availability of Data and Materials: All data is provided in paper.

Competing Interests: The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Consent to Publish: The author agrees to publish the version of the manuscript in this journal.

Ethical Issues: There are no ethical issues.

Funding Statement: N/A.

References

1. Ladd, T.D., F. Jelezko, R. Laflamme, Y. Nakamura, C. Monroe, and J.L. O'Brien, Quantum computers. nature. (2010).464(7285) 45-53.
2. Fauseweh, B., Quantum many-body simulations on digital quantum computers: State-of-the-art and future challenges. Nature Communications. (2024).15(1) 2123.
3. Saffman, M., Quantum computing with neutral atoms. National Science Review. (2019).6(1) 24-25.
4. Proctor, T., K. Young, A.D. Baczewski, and R. Blume-Kohout, Benchmarking quantum computers. Nature Reviews Physics. (2025).7(2) 105-118.

5. Nandhini, S., H. Singh, and U. Akash, An extensive review on quantum computers. Advances in Engineering Software. (2022).174103337.
6. Latten, T.M., M. Sand, and P.E. Vermaas, From Practice To Theory: Three Types of Influence of Quantum Technology on Quantum Mechanics and its Foundations. Foundations of Science. (2025)1-26.
7. Rietsche, R., C. Dremel, S. Bosch, L. Steinacker, M. Meckel, and J.-M. Leimeister, Quantum computing. Electronic Markets. (2022).32(4) 2525-2536.
8. Memon, Q.A., M. Al Ahmad, and M. Pecht, Quantum computing: Navigating the future of computation, challenges, and technological breakthroughs. Quantum Reports. (2024).6(4) 627-663.
9. Gill, S.S., O. Cetinkaya, S. Marrone, D. Claudino, D. Haunschild, L. Schlote, H. Wu, C. Ottaviani, X. Liu, and S.P. Machupalli, Quantum computing: Vision and challenges, in Quantum computing. 2025, Elsevier. p. 19-42.
10. Sood, V. and R.P. Chauhan, Archives of Quantum Computing: Research Progress and Challenges: V. Sood, RP Chauhan. Archives of Computational Methods in Engineering. (2024).31(1) 73-91.
11. Wang, Y., J.E. Kim, and K. Suresh, Opportunities and challenges of quantum computing for engineering optimization. Journal of Computing and Information Science in Engineering. (2023).23(6) 060817.
12. Herzallah, R. and A. Belfakir, From certainty to chance: probabilistic insights into quantum control. The European Physical Journal D. (2024).78(5) 63.
13. Paraskevas, A., Extended Event Calculus using Neutrosophic Logic: Method, Implementation, Analysis, Recent Progress and Future Directions. Neutrosophic Systems with Applications. (2024).1438-49.
14. Firdous, A. and H.K. Maryam, Neutrosophic Logic Reveals Ontological Indeterminacy in Quantum Systems. Journal of Engineering, Science and Technological Trends. (2025).2(3)
15. Biard, H., E. Moreno-Pineda, M. Ruben, E. Bonet, W. Wernsdorfer, and F. Balestro, Increasing the Hilbert space dimension using a single coupled molecular spin. Nature communications. (2021).12(1) 4443.
16. Soiguine, A., The 3-Sphere Instead of Hilbert Space. Journal of Applied Mathematics and Physics. (2022).102733-2742.
17. Filatov, S. and M. Auzinsh, Towards two bloch sphere representation of pure two-qubit states and unitaries. Entropy. (2024).26(4) 280.
18. Iaconis, J., S. Johri, and E.Y. Zhu, Quantum state preparation of normal distributions using matrix product states. npj Quantum Information. (2024).10(1) 15.
19. Tomaz, A.A., R.S. Mattos, and M. Barbatti, The quantum measurement problem: a review of recent trends. Philosophical Magazine. (2025)1-38.
20. Dyte, H.E., G. Gillard, S. Manna, S.F. Covre da Silva, A. Rastelli, and E.A. Chekhovich, Is wave function collapse necessary? explaining quantum nondemolition measurement of a spin qubit within linear evolution. Physical Review Letters. (2024).132(16) 160804.
21. Zenchuk, A.I., W. Qi, A. Kumar, and J. Wu, Matrix manipulations via unitary transformations and ancilla-state measurements. arXiv preprint arXiv:2311.11329. (2023)
22. Kasirajan, V., The quantum superposition principle and bloch sphere representation, in Fundamentals of Quantum Computing: Theory and Practice. 2021, Springer. p. 75-104.
23. Just, B., Quantum gates on one qubit, in Quantum Computing Compact: Spooky Action at a Distance and Teleportation Easy to Understand. 2023, Springer. p. 69-82.
24. Podoshvedov, S.A., Elementary quantum gates in different bases. Quantum Information Processing. (2016).15(10) 3967-3993.
25. Rau, A.R.P., G. Selvaraj, and D. Uskov, Four-level and two-qubit systems, subalgebras, and unitary integration. Physical Review A. (2005).71(6) 062316. 10.1103/PhysRevA.71.062316
26. Marceaux, J. and A. Rau, Mapping qubit algebras to combinatorial designs: JP Marceaux, ARP Rau. Quantum Information Processing. (2020).19(2) 49.
27. Fellous-Asiani, M., J.H. Chai, R.S. Whitney, A. Auffèves, and H.K. Ng, Limitations in quantum computing from resource constraints. PRX Quantum. (2021).2(4) 040335.
28. Desdentado, E., C. Calero, M.Á. Moraga, and F. García, Quantum computing software solutions, technologies, evaluation and limitations: a systematic mapping study: E. Desdentado et al. Computing. (2025).107(5) 110.
29. Al Adeh, F.F., Natural limitations of quantum computing. Int J Swarm Intel Evol Comput. (2017).6(152) 2.
30. Ajagekar, A. and F. You, Quantum computing for energy systems optimization: Challenges and opportunities. Energy. (2019).17976-89.
31. Zhou, Y., E.M. Stoudenmire, and X. Waintal, What limits the simulation of quantum computers? Physical Review X. (2020).10(4) 041038.
32. Pramanik, S., Single-valued neutrosophic set: An overview. Transdisciplinarity. (2022)563-608.
33. Fowler, A.G., Time-optimal quantum computation. arXiv preprint arXiv:1210.4626. (2012)
34. Klimov, P.V., A. Bengtsson, C. Quintana, A. Bourassa, S. Hong, A. Dunsworth, K.J. Satzinger, W.P. Livingston, V. Sivak, and M.Y. Niu, Optimizing quantum gates towards the scale of logical qubits. Nature Communications. (2024).15(1) 2442.
35. Colnaghi, T., G.M. D'Ariano, S. Facchini, and P. Perinotti, Quantum computation with programmable connections between gates. Physics Letters A. (2012).376(45) 2940-2943.
36. Bley, J., E. Rexigel, A. Arias, N. Longen, L. Krupp, M. Kiefer-Emmanouilidis, P. Lukowicz, A. Donhauser, S. Küchemann, and J. Kuhn, Visualizing entanglement in multiqubit systems. Physical Review Research. (2024).6(2) 023077.
37. Grigoryan, E., S. Kumar, and P.R. Pinheiro, A review on models and applications of quantum computing. Quantum Reports. (2025).7(3) 39.
38. Gu, X., J. Fernández-Pendás, P. Vikstål, T. Abad, C. Warren, A. Bengtsson, G. Tancredi, V. Shumeiko, J. Bylander, and G. Johansson, Fast multiqubit gates through simultaneous two-qubit gates. PRX Quantum. (2021).2(4) 040348.
39. Liu, W.Q., H.R. Wei, and L.C. Kwek, Universal Quantum Multi-Qubit Entangling Gates with Auxiliary Spaces. Advanced Quantum Technologies. (2022).5(5) 2100136.

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Journal of Engineering, Science and Technological Trends (JESTT)

Vol. 3, Issue 2, July 2026
DOI: https://doi.org/10.64060/JESTT3i23

Perspective

Nature-Derived Polymers for Next-Generation Sustainable Electronics

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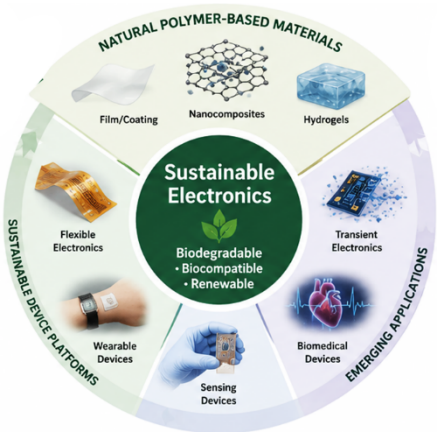
Received: 10 March 2026 / Revised: 09 May 2026 / Accepted: 17 May 2026 / Published online: 16 June 2026

ABSTRACT

The rapid growth of modern electronic technologies has led to a significant increase in electronic waste, posing major environmental and sustainability challenges. Most conventional electronic devices rely on petroleum-based polymers that are non-biodegradable and environmentally persistent, creating an urgent need for sustainable material alternatives. Natural polymers derived from renewable biomass have emerged as promising candidates for next-generation sustainable electronics due to their biodegradability, biocompatibility, abundance, and low environmental impact. This perspective highlights recent progress in natural polymer-based electronic materials, including polysaccharide-based polymers, protein-based polymers, and natural polymer nanocomposites. Their applications in flexible and wearable electronics, transient electronics, and sustainable sensing devices are discussed. Key strategies such as molecular engineering, nanocomposite design, and green processing methods are explored to improve electrical performance and stability. Major challenges, including limited conductivity, moisture sensitivity, thermal stability, and device integration, are also addressed, along with future opportunities for developing fully biodegradable and environmentally friendly electronic systems.



Keywords: Biodegradable electronics; Biopolymer nanocomposites; Flexible electronics; Green electronics; Natural polymers; Sustainable electronics; Transient electronics; Wearable sensors

1. Introduction

The rapid advancement of electronic technologies has profoundly transformed modern society, enabling innovations in communication, healthcare, environmental monitoring, and intelligent systems [1],[2],[3]. The proliferation of consumer electronics, wearable devices, and smart sensing platforms has significantly increased the global demand for electronic materials and components. In most conventional electronic systems, petroleum-derived synthetic polymers are widely used as substrates, encapsulation layers, dielectric materials, and structural components because of their excellent mechanical stability, chemical resistance, and ease of large-scale fabrication [4],[5]. However, the continuous growth of electronic device production has led to an alarming rise in electronic waste (e-waste), which has become one of the fastest-growing waste streams worldwide [6],[7]. The improper disposal and accumulation of non-degradable electronic materials pose serious environmental and ecological challenges, including soil and water contamination and the release of toxic substances during degradation processes. Consequently, the development of environmentally sustainable materials for electronic applications has become a critical priority for researchers and policymakers seeking to reduce the ecological footprint of modern electronic technologies.

Despite the remarkable progress achieved in electronic device engineering, the materials used in most electronic systems

remain largely dependent on non-renewable, petroleum-based polymers that are inherently non-biodegradable and environmentally persistent [8],[9],[10]. These synthetic polymers, such as polyimide, polyethylene terephthalate, and other engineering plastics, provide excellent thermal and mechanical properties but contribute significantly to long-term environmental pollution after disposal. Furthermore, the increasing integration of flexible and wearable electronic devices has intensified the need for materials that are not only mechanically compliant but also environmentally benign. Conventional polymers typically require energy-intensive processing methods and generate substantial carbon emissions during their production lifecycle. Additionally, their long degradation times make recycling and waste management increasingly difficult [11],[12],[13]. These challenges highlight the urgent need to develop alternative materials that combine desirable electronic functionality with sustainability, renewability, and eco-friendly disposal pathways. In this context, natural polymers derived from biomass have emerged as highly promising candidates due to their inherent biodegradability, biocompatibility, and abundant availability [14],[15],[16]. Materials such as cellulose, chitosan, starch, silk fibroin, and gelatin possess unique chemical structures and functional groups that enable tunable physical properties and compatibility with advanced nanomaterials. However, despite their significant potential, several challenges remain in achieving the electrical performance, environmental stability, and large-scale processability required for next-generation electronic devices. As shown in Figure 1, natural biomass sources can be converted into functional polymers and further integrated into electronic device components for sustainable electronics.

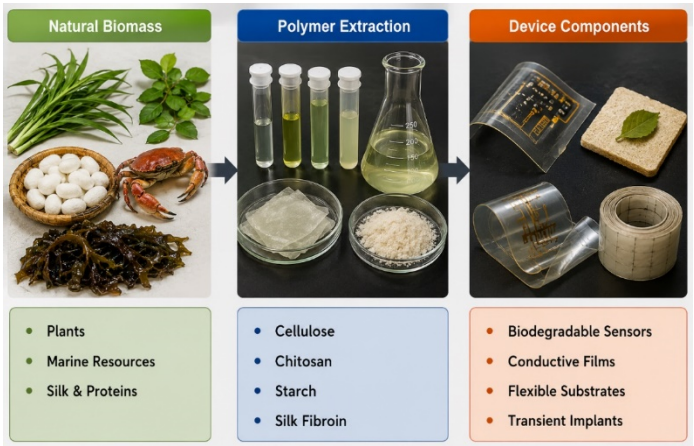


Figure 1: *Schematic illustration of natural biomass sources converted into functional polymers and integrated into electronic device components for sustainable electronics.*

Despite the rapid progress in biodegradable and bio-derived electronic materials, several important research gaps remain in the current literature [17],[18]. Existing reviews often focus on specific material classes, individual device applications, or general biodegradable electronics without providing a comprehensive perspective on the integration of nature-derived polymers, nanocomposite engineering, and sustainable device design strategies for next-generation electronics. In particular, limited attention has been given to correlating the molecular properties of natural polymers with their electrical functionality, environmental stability and scalable fabrication approaches required for practical electronic applications [19]. Furthermore, emerging opportunities involving artificial intelligence-assisted material discovery, transient electronics, and circular electronic design have not been systematically discussed in the context of natural polymer-based electronics. Therefore, this critical review provides a comprehensive and forward-looking overview of nature-derived polymers for sustainable electronics by critically discussing material platforms, nanocomposite strategies, green processing approaches, and emerging device applications. In addition, this review highlights key performance limitations, identifies current technological bottlenecks, and outlines future research directions that may accelerate the development of fully biodegradable and environmentally responsible electronic system.

2. Natural Polymer Platforms for Electronics

Natural polymers derived from renewable biological resources have emerged as promising materials for the development of sustainable electronic devices. Unlike conventional petroleum-based polymers, natural polymers offer intrinsic advantages such as biodegradability, biocompatibility, low toxicity, and environmental sustainability. Their molecular structures typically contain abundant functional groups (e.g., hydroxyl, amino, and carboxyl groups), which enable strong intermolecular interactions, chemical tunability, and compatibility with a wide range of nanomaterials. These characteristics make natural polymers attractive platforms for flexible, biodegradable, and biointegrated electronics. In recent years, significant research efforts have focused on exploiting different classes of natural polymers to fabricate substrates, dielectric layers, sensing elements, and encapsulation materials for next-generation electronic systems. Among these materials, polysaccharide-based polymers, protein-based polymers and natural polymer nanocomposites have received particular attention due to their structural diversity and functional versatility, as mentioned in Figure 2. The following sections discuss these major material classes and highlight their emerging applications in sustainable electronic technologies.

2.1. Polysaccharide-Based Polymers

Polysaccharides represent one of the most abundant classes of natural polymers and are widely distributed in plants, microorganisms, and marine organisms [20],[21]. These macromolecules consist of carbohydrate units connected through glycosidic linkages, forming structurally diverse polymers with tunable mechanical, chemical, and interfacial properties. Owing to their natural abundance, biodegradability, and excellent film-forming ability, polysaccharide-based materials have emerged as promising candidates for sustainable electronic systems. Among them, cellulose, chitosan, starch, and alginate have been extensively explored for applications in flexible electronics, dielectric layers, and sensing platforms.

Cellulose is the most abundant biopolymer on Earth and has attracted considerable interest as a sustainable substrate for electronic devices [22],[23],[24]. Composed of linear β-(1→4) linked glucose units, cellulose forms highly ordered crystalline domains through strong hydrogen-bonding networks, resulting in excellent mechanical strength, flexibility, and chemical stability. Cellulose can be processed into films, nanopaper, and nanofiber networks that function as flexible substrates for printed electronics and wearable devices. In addition, cellulose derivatives such as cellulose acetate and carboxymethyl cellulose exhibit favourable dielectric properties and can be processed using environmentally friendly solution-based techniques. Chitosan, derived from the deacetylation of chitin found in crustacean shells, is another important polysaccharide for electronic applications [25]. Its intrinsic biocompatibility, biodegradability, and reactive amino groups enable facile chemical modification and functionalization.

Chitosan has been widely utilised as a dielectric layer in organic field-effect transistors and as a functional matrix for biosensors [26],[27]. The incorporation of conductive nanomaterials such as graphene or metal nanoparticles further enhances electrical conductivity and sensing performance. Starch and alginate also provide attractive platforms for biodegradable electronics [28],[29]. Modified starch materials can be processed into flexible films serving as substrates or encapsulation layers, while alginate hydrogels, formed through ionic crosslinking, offer soft and biocompatible interfaces for wearable sensors and bioelectronic devices. Collectively, polysaccharide-based materials provide versatile and sustainable building blocks for next-generation, environmentally friendly electronic technologies.

2.2. Protein-Based Polymers

Protein-based polymers represent another important class of natural materials for sustainable electronic applications [30],[31]. Proteins consist of amino acid building blocks linked through peptide bonds, forming hierarchical structures with diverse mechanical and functional properties. Due to their inherent biocompatibility, biodegradability, and mechanical flexibility, protein-based materials have attracted significant interest for biointegrated electronic systems. Among them, silk fibroin, gelatin, and collagen have been widely investigated for applications in wearable electronics, bioelectronics, and implantable sensing devices.

Silk fibroin, derived from silkworm cocoons, is one of the most promising protein-based materials for electronic applications [32],[33]. It exhibits excellent mechanical strength, optical transparency, and biodegradability, along with outstanding biocompatibility. Silk fibroin can be processed into thin films through simple solution-based methods and has been widely used as flexible substrates, dielectric layers, and structural materials in transient electronic devices. These properties enable the development of electronic systems that can safely degrade after completing their function. In addition, silk can be integrated with conductive nanomaterials to form hybrid materials for biosensing platforms and flexible circuits. Gelatin, obtained from the partial hydrolysis of collagen, is another widely utilised protein polymer [34]. It forms flexible films and hydrogels with tunable mechanical properties, making it suitable for wearable sensors and soft electronic devices. The presence of amino and carboxyl functional groups enables chemical modification and incorporation of conductive nanomaterials, improving electrical conductivity and sensing performance. Collagen, the most abundant structural protein in the human body, also provides an attractive platform for sustainable electronics [35],[36]. Its excellent biocompatibility and ability to form porous scaffolds or hydrogels make it particularly suitable for implantable sensors, tissue-interfacing electronics, and biosensing systems.

2.3. Biopolymer Nanocomposites

Natural polymers offer many advantages for sustainable electronics; however, their intrinsically low electrical conductivity limits their direct application in devices requiring efficient charge transport [37],[38]. To address this challenge, significant research efforts have focused on the development of biopolymer nanocomposites, where natural polymers are combined with conductive nanomaterials. This strategy enables the integration of the flexibility, biodegradability, and environmental compatibility of

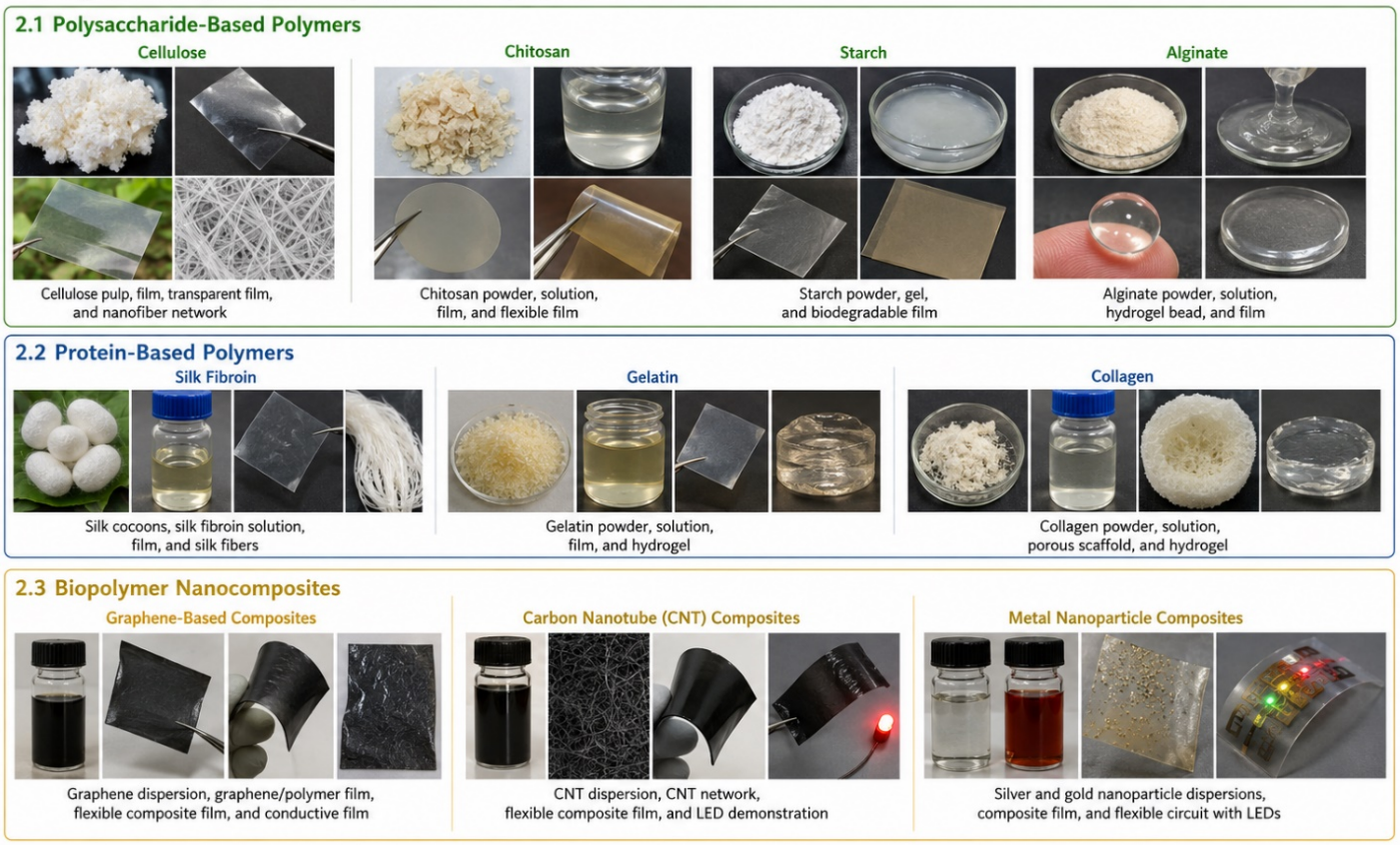


Figure 2: *Representative natural polymer platforms for sustainable electronics, including polysaccharide-based polymers (cellulose, chitosan, starch, and alginate), protein-based polymers (silk fibroin, gelatin, and collagen), and biopolymer nanocomposites integrated with graphene, carbon nanotubes (CNTs), and metal nanoparticles. The figure highlights real material forms, processing characteristics, and their potential applications in flexible, biodegradable, wearable, and biointegrated electronic devices.*

natural polymers with the excellent electrical properties of advanced nanomaterials. Graphene is one of the most widely used conductive nanomaterials in biopolymer composites [39],[40]. Owing to its exceptional electrical conductivity, large surface area, and mechanical strength, graphene can significantly enhance the electrical performance of natural polymer matrices. Strong interfacial interactions between graphene sheets and polymer chains contribute to improved mechanical stability and conductivity, enabling applications in flexible sensors, wearable electronics, and biodegradable conductive films. Carbon nanotubes (CNTs) are also extensively employed due to their high aspect ratio and outstanding electrical properties [41],[42]. When incorporated into natural polymer matrices, CNTs form interconnected conductive pathways that dramatically improve charge transport. Such composites have been explored for strain sensors, gas sensors, and flexible electronic circuits.

Metal nanoparticles, including silver and gold, further enhance conductivity and sensing performance through catalytic and electron transfer effects [43],[44]. Overall, natural polymer–nanomaterial composites provide a promising pathway toward high-performance, environmentally friendly electronic systems.

3. Emerging Device Applications

The integration of natural polymers into electronic materials has opened new opportunities for the development of sustainable and environmentally friendly electronic systems [37],[45],[46]. In recent years, increasing attention has been directed toward designing devices that are not only high-performing but also biodegradable, biocompatible, and environmentally responsible. Natural polymers offer unique advantages for these applications due to their mechanical flexibility, chemical functionality, and compatibility with solution-based fabrication techniques, as shown in Figure 3. Moreover, their ability to form thin films, hydrogels, and nanostructured composites enables the fabrication of lightweight and flexible electronic platforms. As a result, natural polymer-based materials are increasingly being explored in several emerging device applications, including flexible and wearable electronics, transient electronics, and sustainable sensing technologies. These developments represent important steps toward the realisation of next-generation green electronics that can minimise environmental impact while maintaining functional performance.

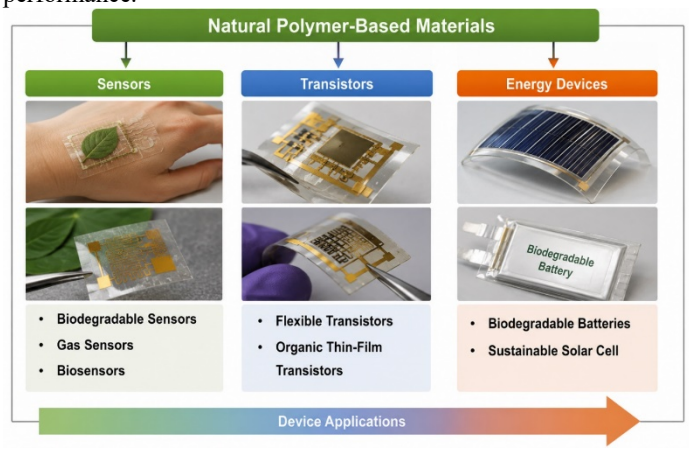


Figure 3: *Device applications of natural polymer-based materials for sustainable electronics, including sensors, transistors and energy devices such as biodegradable batteries and solar cells.*

3.1. Flexible and Wearable Electronics

Flexible and wearable electronics have emerged as a major technological direction in modern electronic systems [2],[47],[48]. These devices are designed to conform to curved surfaces, human skin, or soft biological tissues while maintaining stable electrical performance under mechanical deformation. Traditional electronic materials are generally rigid and brittle, limiting their use in flexible platforms. In contrast, natural polymers possess intrinsic flexibility, low elastic modulus, and excellent film-forming capability, making them attractive materials for mechanically compliant electronic devices.

Natural polymer-based materials have been widely explored as substrates and functional components in flexible electronics [37]. Polymers such as cellulose, silk fibroin, and gelatin can be processed into thin, lightweight films that provide mechanical support while maintaining bendability. When combined with conductive nanomaterials, including graphene, carbon nanotubes, and metallic nanostructures, these materials enable the fabrication of flexible electronic circuits and sensing elements. Such hybrid systems can withstand repeated bending, stretching, and mechanical deformation without significant performance degradation.

Biodegradable sensors represent one of the most promising applications of natural polymer-based flexible electronics [49],[50]. These devices can detect physical, chemical, or biological signals while reducing environmental impact after disposal. Natural polymer substrates support conductive sensing layers capable of responding to stimuli such as gases, humidity, temperature, or mechanical strain, making them suitable for environmental monitoring and disposable healthcare devices.

Another rapidly developing area is skin-like electronics. Natural polymers such as silk fibroin and gelatin exhibit softness and biocompatibility similar to human skin, enabling intimate contact with the body [51],[52]. Flexible electronic patches based on these materials have been developed to monitor physiological signals, including heart rate, body temperature, and motion. Such systems provide promising opportunities for continuous, non-invasive health monitoring and next-generation wearable technologies.

3.2. Transient Electronics

Transient electronics represent a rapidly growing field that focuses on electronic devices designed to physically disappear or degrade after completing their intended function [53],[54]. Unlike conventional electronic systems that persist in the environment for long periods, transient electronics are engineered to dissolve in water or biological fluids, thereby eliminating electronic waste and enabling new biomedical applications. Natural polymers are particularly attractive materials for transient electronics because of their inherent biodegradability and environmentally friendly degradation pathways.

Natural polymer-based transient electronic devices can be fabricated using materials such as cellulose, silk fibroin, and chitosan, which gradually degrade under specific environmental conditions [55],[56]. These materials can serve as substrates, dielectric layers, or encapsulation materials for electronic circuits that are designed to operate for a predetermined period before dissolving. By carefully controlling the thickness, crystallinity, and chemical modification of the polymer matrix, researchers can tune the degradation rate of these materials to match the desired device lifetime.

One of the most important applications of transient electronics is in the field of biomedical implants. Temporary electronic implants can be used to monitor physiological signals, deliver therapeutic stimulation, or assist in tissue healing following surgery [57]. After the required monitoring or treatment period, the device gradually degrades inside the body, eliminating the need for surgical removal. Natural polymer substrates provide excellent

biocompatibility and minimise adverse immune responses, making them ideal materials for such implantable electronic systems.

Environmental monitoring is another promising application area for transient electronics [53],[58]. In many cases, electronic sensors are deployed in natural environments such as forests, oceans, or agricultural fields to monitor environmental conditions. However, retrieving these devices after use can be difficult or impractical, leading to the accumulation of electronic waste. Transient electronics fabricated from biodegradable polymers offer a sustainable alternative, as they can naturally degrade after completing their monitoring tasks. Such systems can be used for temporary environmental sensing, disaster monitoring, or agricultural data collection without leaving long-term electronic debris.

3.3. Sustainable Sensors

Among the various applications of natural polymer electronics, sustainable sensing technologies have received significant research attention. Sensors play a critical role in modern electronic systems by enabling the detection and monitoring of environmental, chemical, and biological signals [59],[60],[61]. However, the widespread deployment of sensing devices has raised concerns regarding material sustainability and electronic waste generation. Natural polymer-based sensing platforms offer a promising solution by combining high sensitivity with environmental compatibility.

Natural polymer composites have been extensively investigated as sensing materials due to their ability to interact with analyte molecules through functional chemical groups [50],[62]. Polymers such as chitosan, cellulose, and gelatin contain abundant hydroxyl, amino, and carboxyl groups that can form interactions with various chemical species. These interactions can induce changes in electrical conductivity, capacitance, or optical properties, which can be detected as sensor signals. Gas sensors based on natural polymer composites have demonstrated considerable potential for environmental monitoring and industrial safety applications [63]. By incorporating conductive nanomaterials such as graphene or carbon nanotubes into natural polymer matrices, researchers have developed highly sensitive gas sensors capable of detecting pollutants such as ammonia, nitrogen dioxide, and volatile organic compounds [64],[65]. The polymer matrix provides a flexible and biodegradable support structure, while the conductive nanomaterials enable efficient electrical signal transduction. Humidity sensors represent another important category of sustainable sensing devices [66]. Many natural polymers exhibit strong interactions with water molecules due to their hydrophilic functional groups [67]. These interactions lead to measurable changes in electrical resistance, capacitance, or dielectric properties when exposed to varying humidity levels. As a result, natural polymer-based humidity sensors have been widely investigated for applications in environmental monitoring, smart packaging, and wearable electronics. Biosensors based on natural polymers are also gaining increasing importance in healthcare and biomedical diagnostics [68]. Natural polymers provide a biocompatible environment for immobilising enzymes, antibodies, or other biomolecules that can selectively detect biological analytes. These sensing platforms can be used for monitoring glucose levels, detecting pathogens, or analysing biomarkers in bodily fluids. The combination of biocompatibility, flexibility, and biodegradability makes natural polymer-based biosensors particularly attractive for next-generation medical diagnostics and wearable health monitoring systems.

Overall, the development of emerging device applications based on natural polymer materials represents a major step toward sustainable electronic technologies. Flexible and wearable electronics, transient electronic systems, and sustainable sensing platforms demonstrate how natural polymers can be integrated into functional electronic devices while reducing environmental impact. Continued research in this area is expected to further enhance device performance, expand application possibilities, and accelerate the transition toward environmentally responsible electronic systems.

4. Comparing Cocrystals Protonated through Acidic Stimulation

The successful implementation of natural polymers in sustainable electronic devices requires careful material design and engineering strategies. Although natural polymers possess attractive properties such as biodegradability, flexibility, and biocompatibility, their direct use in electronic devices is often limited by challenges, including low electrical conductivity, poor moisture stability, and limited thermal resistance [37]. To overcome these limitations and enhance device performance, several design strategies have been developed. These strategies focus on modifying the molecular structure of natural polymers, integrating them with functional nanomaterials, and employing environmentally friendly fabrication methods. Among the most important approaches are molecular engineering, nanocomposite design, and green processing techniques. Together, these strategies provide a comprehensive framework for developing high-performance natural polymer-based electronic materials.

4.1. Molecular Engineering

Molecular engineering plays a critical role in tailoring the structural and functional properties of natural polymers for electronic applications [38],[69]. Natural polymers typically contain reactive functional groups such as hydroxyl, amino, and carboxyl groups, which provide opportunities for chemical modification. By introducing new functional groups or altering the polymer network structure, researchers can significantly improve the electrical, mechanical, and chemical properties of these materials.

Functionalization is one of the most widely used molecular engineering strategies [69]. Through chemical modification, functional molecules or conductive groups can be attached to the polymer backbone, enabling enhanced interactions with analyte molecules or conductive nanomaterials [70]. For example, functionalized cellulose and chitosan derivatives have been used to improve the sensitivity of gas sensors and biosensors. Functionalization can also improve interfacial compatibility between natural polymers and conductive fillers, leading to improved electrical performance in composite materials.

Crosslinking is another important strategy for improving the stability and mechanical strength of natural polymer networks. Crosslinking involves forming chemical or physical bonds between polymer chains, which enhances the structural integrity of the material [71]. This approach can improve thermal stability, reduce water solubility, and increase the durability of polymer films used in electronic devices. For example, crosslinked gelatin or chitosan hydrogels have been widely used in flexible electronics and bioelectronic interfaces due to their improved mechanical properties and stability under environmental conditions [42].

4.2. Nanocomposite Design

Nanocomposite engineering has emerged as a powerful approach for enhancing the electrical functionality of natural polymer materials [72],[73]. Since most natural polymers are electrically insulating, the incorporation of conductive nanomaterials is essential for enabling electronic device operation.

Nanocomposite design involves dispersing conductive fillers within a natural polymer matrix to create hybrid materials with improved electrical conductivity and sensing performance. Common conductive fillers include graphene, carbon nanotubes, metal nanoparticles, and conductive polymers [74],[75],[76]. These nanomaterials provide efficient pathways for electron transport, allowing the composite material to exhibit significantly improved electrical conductivity. In addition, the high surface area of nanomaterials facilitates strong interactions with gas molecules, biomolecules, or environmental stimuli, which enhances the sensitivity of sensing devices. The performance of nanocomposite materials depends strongly on factors such as filler dispersion, interfacial bonding, and the formation of conductive networks within the polymer matrix [77],[78]. Uniform dispersion of nanomaterials within the polymer is essential to achieve consistent electrical properties and mechanical stability. Researchers often employ surface modification techniques or polymer functionalization to improve compatibility between the polymer matrix and conductive fillers. As a result, natural polymer nanocomposites have demonstrated excellent performance in applications such as gas sensors, strain sensors, flexible electronics, and wearable sensing devices.

4.3. Green Processing

In addition to material design, fabrication techniques play a crucial role in determining the sustainability and scalability of natural polymer electronics. Green processing methods aim to minimise environmental impact by reducing energy consumption, eliminating toxic solvents, and enabling low-temperature fabrication processes [79],[80]. Natural polymers are particularly well-suited for green processing because they can often be dissolved or dispersed in water or other environmentally benign solvents.

Table 1
Key Design Strategies for Natural Polymer-Based Sustainable Electronics

Strategy	Key Methods	Purpose	Example Applications
Molecular Engineering	Functionalization, Crosslinking	Improve chemical stability, mechanical strength, and interfacial interactions.	Flexible electronics, biosensors, dielectric layers
Nanocomposite Design	Incorporation of graphene, carbon nanotubes and metal nanoparticles	Enhance electrical conductivity and sensing performance	Gas sensors, strain sensors and wearable devices
Green Processing	Printing electronics, solution processing	Enable scalable, low-cost, and environmentally friendly fabrication	Printed sensors, flexible circuits, biodegradable electronics

Printing electronics is one of the most promising fabrication strategies for natural polymer-based devices [45],[81]. Techniques such as inkjet printing, screen printing, and roll-to-roll printing allow the direct deposition of functional materials onto flexible substrates. These methods enable large-area device fabrication while minimising material waste and processing complexity. Natural polymer inks containing conductive nanomaterials can be printed to form electronic circuits, sensors, or electrode structures for various applications. Solution processing is another widely used technique for fabricating natural polymer electronic materials [82]. Many natural polymers can be processed from aqueous solutions, allowing thin films or coatings to be formed through methods such as spin coating, drop casting, or dip coating. These techniques are relatively simple, cost-effective, and compatible with flexible substrates. Furthermore, solution-based fabrication enables easy integration of nanomaterials and functional additives, which can enhance the performance of the resulting electronic devices.

Overall, the combination of molecular engineering, nanocomposite design, and green processing strategies provides a comprehensive approach to developing high-performance natural polymer-based electronics. By carefully optimising these design strategies, researchers can overcome the inherent limitations of natural polymers while preserving their environmental advantages, as mentioned in Table 1. Continued progress in these areas is expected to accelerate the development of sustainable electronic technologies capable of addressing both performance and environmental challenges.

5. Key Challenges

Despite significant progress in natural polymer-based sustainable electronics, several critical challenges continue to limit their large-scale commercialisation and practical implementation in advanced electronic systems. One of the major limitations is the inherently low electrical conductivity of most natural polymers. Materials such as cellulose, chitosan, starch, and protein-based polymers are electrically insulating because they lack extended conjugated electron transport pathways. Although the incorporation of conductive nanomaterials, including graphene, carbon nanotubes, conductive polymers, and metal nanoparticles, can significantly improve electrical conductivity, achieving homogeneous dispersion and stable conductive networks within the polymer matrix remains challenging. Agglomeration of nanofillers, poor interfacial compatibility, and inconsistent electrical pathways can result in reduced device performance, signal instability, and limited reproducibility.

Mechanical stability is another important concern, particularly for flexible and wearable electronic devices subjected to repeated bending, stretching, and deformation. Many natural polymers exhibit relatively weak mechanical strength, low fracture resistance, and structural degradation under cyclic mechanical loading. In addition, environmental exposure to humidity and temperature fluctuations can further weaken polymer structures due to water absorption and swelling effects. These issues may lead to cracking, delamination, or degradation of conductive interfaces during long-term operation. Therefore, improving the mechanical robustness and fatigue resistance of natural polymer composites remains essential for reliable device performance.

Scalability and large-scale manufacturing also represent major challenges for the practical adoption of natural polymer electronics. Although laboratory-scale fabrication methods such as solution casting, spin coating, and printing techniques have demonstrated promising results, translating these approaches to industrial-scale manufacturing remains difficult. Variations in natural biomass sources, purification processes, molecular structure, and material consistency can lead to batch-to-batch variability and inconsistent device performance. Furthermore, many natural polymers require additional chemical modification, crosslinking, or nanocomposite engineering to achieve suitable electronic functionality, which can increase processing complexity and production cost. The compatibility of natural polymers with

existing semiconductor manufacturing infrastructure also remains limited in many cases.

Long-term operational reliability is another critical issue for sustainable electronic systems based on natural polymers. Compared with conventional engineering polymers, natural polymer materials often exhibit lower thermal stability, higher moisture sensitivity, and accelerated degradation under environmental stress conditions such as heat, ultraviolet radiation, and oxidation. These factors can significantly affect the electrical stability, sensing accuracy, and lifetime of electronic devices during prolonged use. In biodegradable and transient electronics, balancing controlled degradation behaviour with sufficient operational lifetime remains particularly challenging. Achieving stable performance while maintaining environmental degradability requires careful optimisation of polymer chemistry, encapsulation strategies, and device architecture.

Addressing these challenges will require interdisciplinary efforts involving materials science, nanotechnology, chemical engineering, and device physics. Future research should focus on developing highly conductive bio-derived materials, improving interfacial engineering, enhancing environmental stability, and establishing scalable green manufacturing methods capable of supporting commercial production of sustainable electronic devices.

6. Future Opportunities

Despite these challenges, natural polymer-based electronics represent an exciting and rapidly evolving research field with significant potential for future technological development. Continued advances in materials science, nanotechnology, and sustainable manufacturing are expected to enable new solutions that overcome current limitations and unlock the full potential of natural polymer platforms. Several promising research directions have emerged that could significantly accelerate the development of sustainable electronic technologies, including bio-derived conductive polymers, artificial intelligence-assisted material discovery, fully biodegradable electronic systems, and circular electronic design strategies, as mentioned in Figure 4.

Figure 4: *Future roadmap for natural polymer-based sustainable electronics. Current challenges, including low electrical conductivity, moisture instability, limited thermal stability, and device integration issues, can be addressed through emerging solutions such as bio-derived conductive polymers, artificial intelligence-assisted materials discovery, and circular electronic design, ultimately enabling next-generation sustainable electronic technologies.*

Several promising research directions are emerging to advance natural polymer–based sustainable electronics. One key approach involves the development of bio-derived conductive polymers that combine the environmental advantages of natural materials with the electrical functionality required for electronic devices. Introducing conjugated structures or conductive pathways through chemical modification and hybrid material design can significantly improve charge transport. For example, integrating natural polymers with intrinsically conductive polymers or bio-inspired conductive molecules may produce materials that retain biodegradability while exhibiting enhanced electrical performance for sensors, flexible electronics, and energy devices.

- Artificial intelligence and machine learning are also becoming valuable tools for accelerating the discovery and optimisation of natural polymer materials. By analysing large datasets related to polymer structures, nanocomposite formulations, and device performance, AI-driven models can predict promising material combinations and processing strategies. This approach can significantly reduce experimental time and enable the rapid development of high-performance sustainable electronic materials.
- Another important direction is the development of fully biodegradable electronic systems. Achieving this goal requires environmentally friendly alternatives for all device components, including electrodes, semiconductors, and energy storage materials. Such systems could enable transient medical implants, disposable sensors, and eco-friendly electronic platforms.
- In addition, the concept of circular electronics emphasises recyclability, renewable materials, and closed-loop manufacturing. Natural polymers are well-suited for this approach due to their renewable origin and natural degradability, supporting the development of environmentally responsible electronic technologies.

7. Conclusion

Natural polymer-based materials have emerged as highly promising candidates for next-generation sustainable electronic technologies due to their biodegradability, biocompatibility, renewability, and low environmental impact. This review highlights the significant progress achieved in the development of nature-derived polymers such as cellulose, chitosan, starch, alginate, silk fibroin, gelatin, and collagen for applications in flexible electronics, wearable devices, transient electronics, and sustainable sensing systems. The integration of these polymers with conductive nanomaterials, including graphene, carbon nanotubes, and metal nanoparticles, has substantially improved their electrical performance, mechanical flexibility, and sensing capabilities, enabling environmentally friendly alternatives to conventional petroleum-based electronic materials. In addition, advances in molecular engineering, nanocomposite design, and green fabrication methods have demonstrated strong potential for enhancing device functionality and scalability. However, several challenges, including low intrinsic conductivity, moisture sensitivity, limited thermal and mechanical stability, scalability issues, and long-term operational reliability, still restrict large-scale practical implementation. Future research should therefore focus on developing bio-derived conductive materials, improving interfacial engineering and environmental stability, establishing scalable green manufacturing strategies, and designing fully biodegradable electronic systems with controlled degradation behaviour. Furthermore, emerging approaches such as artificial intelligence-assisted material discovery and circular electronic manufacturing may accelerate the development of high-performance and commercially viable sustainable electronics. Overall, continued interdisciplinary research combining materials science, nanotechnology, chemistry, and device engineering is expected to

play a crucial role in advancing nature-derived polymers toward environmentally responsible next-generation electronic technologies.

Declaration

AI Disclosure: N/A

Author Contribution Statement: A. N. and A. U. equally work on this paper.

Availability of Data and Materials: Data will be made available by the corresponding author on reasonable request.

Competing Interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Consent to Publish: The authors agree to publish the version of the manuscript in this journal.

Ethical Issues: There are no ethical issues.

References

1. Thacharodi, A., P. Singh, R. Meenatchi, Z. Tawfeeq Ahmed, R.R. Kumar, N. V, S. Kavish, M. Maqbool, and S. Hassan, Revolutionizing healthcare and medicine: The impact of modern technologies for a healthier future—A comprehensive review. Health Care Science. (2024).3(5) 329-349.
2. Wang, P., M. Hu, H. Wang, Z. Chen, Y. Feng, J. Wang, W. Ling, and Y. Huang, The evolution of flexible electronics: from nature, beyond nature, and to nature. Advanced Science. (2020).7(20) 2001116.
3. Madsen, K.E., M.T. Flavin, and J.A. Rogers, Materials advances for distributed environmental sensor networks at scale. Nature Reviews Materials. (2026).11(1) 26-49.
4. Yu, P.-J., Y.-C. Lin, and W.-C. Chen, Review of bioderived and biodegradable polymers/block-copolymers and their biomedical and electronic applications. Polymer Journal. (2025).57(3) 233-247.
5. Ates, B., S. Koytepe, A. Ulu, C. Gurses, and V.K. Thakur, Chemistry, structures, and advanced applications of nanocomposites from biorenewable resources. Chemical reviews. (2020).120(17) 9304-9362.
6. Heacock, M., C.B. Kelly, K.A. Asante, L.S. Birnbaum, Å.L. Bergman, M.-N. Bruné, I. Buka, D.O. Carpenter, A. Chen, and X. Huo, E-waste and harm to vulnerable populations: a growing global problem. Environmental health perspectives. (2015).124(5) 550.
7. Parvez, S.M., Electronic waste is a public health crisis that demands urgent action. Nature Human Behaviour. (2025).9(11) 2215-2216.
8. Sharma, B.K., A. Jha, D. Bhalani, S.A. Pillai, S. Pal, K. Patil, and K. Nagaraj, Advancements in bio-resource-based polymers and composites: sustainable alternatives to non-biodegradable plastics for a greener future: A review. Current Green Chemistry. (2025)
9. Kothawade, S.N., V.V. Pande, J. Suryawanshi, A. Kumar, P. Kumar, and A. Kumar, Biodegradable and Non-Biodegradable Sustainable Biomaterials, in Advances in Sustainable Biomaterials. 2024, CRC Press. p. 92-116.
10. Kamran, F., H. Afshar, and F. Shahi, Recent advances and applications of sustainable and recyclable polymers. Polymer Engineering & Science. (2025).65(8) 3845-3879.
11. Dey, S., G. Veerendra, P.A. Babu, A.P. Manoj, and K. Nagarjuna, Degradation of plastics waste and its effects on biological ecosystems: A scientific analysis and comprehensive review. Biomedical Materials & Devices. (2024).2(1) 70-112.
12. Rahimi, A. and J.M. García, Chemical recycling of waste plastics for new materials production. Nature Reviews Chemistry. (2017).1(6) 0046.
13. Law, K.L. and R. Narayan, Reducing environmental plastic pollution by designing polymer materials for managed end-of-life. Nature Reviews Materials. (2022).7(2) 104-116.
14. Silva, A.C., A.J. Silvestre, C. Vilela, and C.S. Freire, Natural polymers-based materials: A contribution to a greener future. Molecules. (2021).27(1) 94.
15. Samir, A., F.H. Ashour, A.A. Hakim, and M. Bassyouni, Recent advances in biodegradable polymers for sustainable applications. Npj Materials Degradation. (2022).6(1) 68.
16. Wu, L., X. Shi, and Z.S. Wu, Recent advancements and perspectives of biodegradable polymers for supercapacitors. Advanced Functional Materials. (2023).33(16) 2211454.
17. Teixeira, S.C., N.O. Gomes, T.V. de Oliveira, P. Fortes-Da-Silva, N.d.F.F. Soares, and P.A. Raymundo-Pereira, Review and Perspectives of sustainable, biodegradable, eco-friendly and flexible electronic devices and (Bio) sensors. Biosensors and Bioelectronics: X. (2023).14100371.
18. Ozlu, B., M.B. Ahmed, R.M. Muthoka, Z. Wen, Y. Bea, J.H. Youk, Y. Lee, M.H. Yoon, and B.S. Shim, Naturally derived electrically active materials for eco-friendly electronics. Materials Today Advances. (2024).21100470.
19. Gonçalves, R., J. Serra, A. Reizabal, D. Correia, L. Fernandes, R. Brito-Pereira, E. Lizundia, C. Costa, and S. Lanceros-Méndez, Biobased polymers for advanced applications: Towards a sustainable future. Progress in Polymer Science. (2025).162101934.
20. Li, Z. and Z. Lin, Recent advances in polysaccharide-based hydrogels for synthesis and applications. Aggregate. (2021).2(2) e21.
21. Sahu, A., M. Adnan Raza, N. Khatoon, M.K. Sharma, and Ajazuddin, Polysaccharide-based polymers for designing thermoresponsive hydrogels for treating wound healing. ACS Applied Bio Materials. (2025).8(12) 10549-10575.
22. Shaghaleh, H., X. Xu, and S. Wang, Current progress in production of biopolymeric materials based on cellulose, cellulose nanofibers, and cellulose derivatives. RSC advances. (2018).8(2) 825-842.
23. Ye, Y., L. Yu, E. Lizundia, Y. Zhu, C. Chen, and F. Jiang, Cellulose-based ionic conductor: an emerging material toward sustainable devices. Chemical Reviews. (2023).123(15) 9204-9264.
24. Klemm, D., B. Heublein, H.P. Fink, and A. Bohn, Cellulose: fascinating biopolymer and sustainable raw material. Angewandte chemie international edition. (2005).44(22) 3358-3393.
25. Suginta, W., P. Khunkaewla, and A. Schulte, Electrochemical biosensor applications of polysaccharides chitin and chitosan. Chemical reviews. (2013).113(7) 5458-5479.
26. Song, J., H. Liu, Z. Zhao, P. Lin, and F. Yan, Flexible organic transistors for biosensing: devices and applications. Advanced Materials. (2024).36(20) 2300034.
27. Chauhan, S. and A. Thakur, Chitosan-based biosensors-A comprehensive Review. Materials Today: Proceedings. (2023)
28. Xiang, H., Z. Li, H. Liu, T. Chen, H. Zhou, and W. Huang, Green flexible electronics based on starch. npj Flexible Electronics. (2022).6(1) 15.
29. Teng, K., Q. An, Y. Chen, Y. Zhang, and Y. Zhao, Recent development of alginate-based materials and their versatile functions in biomedicine, flexible electronics, and environmental uses. ACS Biomaterials Science & Engineering. (2021).7(4) 1302-1337.
30. Miserez, A., J. Yu, and P. Mohammadi, Protein-based biological materials: molecular design and artificial production. Chemical reviews. (2023).123(5) 2049-2111.
31. Yorke, S.K., Z. Yang, E.G. Wiita, A. Kamada, T.P. Knowles, and M.J. Buehler, Design and sustainability of polypeptide material systems. Nature Reviews Materials. (2025).10(10) 750-768.
32. Wen, D.-L., D.-H. Sun, P. Huang, W. Huang, M. Su, Y. Wang, M.-D. Han, B. Kim, J. Brugger, and H.-X. Zhang, Recent progress in silk fibroin-based flexible electronics. Microsystems & nanoengineering. (2021).7(1) 35.
33. Huang, W., S. Ling, C. Li, F.G. Omenetto, and D.L. Kaplan, Silkworm silk-based materials and devices generated using bio-nanotechnology. Chemical Society Reviews. (2018).47(17) 6486-6504.
34. Alipal, J., N.M. Pu'Ad, T.C. Lee, N. Nayan, N. Sahari, H. Basri, M. Idris, and H. Abdullah, A review of gelatin: Properties, sources, process, applications, and commercialisation. Materials Today: Proceedings. (2021).42240-250.
35. Liu, X., C. Zheng, X. Luo, X. Wang, and H. Jiang, Recent advances of collagen-based biomaterials: Multi-hierarchical structure, modification and biomedical applications. Materials Science and Engineering: C. (2019).991509-1522.

36. Zhang, X., J. Liu, L. Li, X. Zheng, K. Tang, and Y. Pei, Collagen-Based Flexible Electronic Devices for Electrochemical Energy Storage and Sensing. Macromolecular Rapid Communications. (2023).44(10) 2200977.
37. Gao, D., J. Lv, and P.S. Lee, Natural polymer in soft electronics: opportunities, challenges, and future prospects. Advanced Materials. (2022).34(25) 2105020.
38. Cui, X., M. Wu, X. Liu, B. He, Y. Zhu, Y. Jiang, and Y. Yang, Engineering organic polymers as emerging sustainable materials for powerful electrocatalysts. Chemical Society Reviews. (2024).53(3) 1447-1494.
39. Rouf, T.B. and J.L. Kokini, Biodegradable biopolymer–graphene nanocomposites. Journal of Materials Science. (2016).51(22) 9915-9945.
40. Sharma, S., B. Sharma, and P. Jain, Graphene based biopolymer nanocomposites in sensors, in Graphene Based Biopolymer Nanocomposites. 2020, Springer. p. 273-286.
41. Zhang, X., W. Lu, G. Zhou, and Q. Li, Understanding the mechanical and conductive properties of carbon nanotube fibers for smart electronics. Advanced Materials. (2020).32(5) 1902028.
42. Fenta, E.W. and B.A. Mebratie, Advancements in carbon nanotube-polymer composites: Enhancing properties and applications through advanced manufacturing techniques. Heliyon. (2024).10(16)
43. Metz, K.M., S.E. Sanders, J.P. Pender, M.R. Dix, D.T. Hinds, S.J. Quinn, A.D. Ward, P. Duffy, R.J. Cullen, and P.E. Colavita, Green synthesis of metal nanoparticles via natural extracts: the biogenic nanoparticle corona and its effects on reactivity. ACS Sustainable Chemistry & Engineering. (2015).3(7) 1610-1617.
44. Musa, A.A., A. Bello, S.M. Adams, A.P. Onwualu, V.C. Anye, K.A. Bello, and I.I. Obianyo, Nano-enhanced polymer composite materials: a review of current advancements and challenges. Polymers. (2025).17(7) 893.
45. Hui, Z., L. Zhang, G. Ren, G. Sun, H.D. Yu, and W. Huang, Green flexible electronics: natural materials, fabrication, and applications. Advanced Materials. (2023).35(28) 2211202.
46. Li, W., Q. Liu, Y. Zhang, C.a. Li, Z. He, W.C. Choy, P.J. Low, P. Sonar, and A.K.K. Kyaw, Biodegradable materials and green processing for green electronics. Advanced materials. (2020).32(33) 2001591.
47. Baeg, K.J. and J. Lee, Flexible electronic systems on plastic substrates and textiles for smart wearable technologies. Advanced Materials Technologies. (2020).5(7) 2000071.
48. Xu, K., Y. Lu, and K. Takei, Multifunctional skin-inspired flexible sensor systems for wearable electronics. Advanced Materials Technologies. (2019).4(3) 1800628.
49. Min, J., Y. Jung, J. Ahn, J.G. Lee, J. Lee, and S.H. Ko, Recent advances in biodegradable green electronic materials and sensor applications. Advanced Materials. (2023).35(52) 2211273.
50. Alam, M.W., S. Islam Bhat, H.S. Al Qahtani, M. Aamir, M.N. Amin, M. Farhan, S. Aldabal, M.S. Khan, I. Jeelani, and A. Nawaz, Recent progress, challenges, and trends in polymer-based sensors: a review. Polymers. (2022).14(11) 2164.
51. Wang, C., T. Yokota, and T. Someya, Natural biopolymer-based biocompatible conductors for stretchable bioelectronics. Chemical Reviews. (2021).121(4) 2109-2146.
52. Shaji, S., A. Anna, S. Kiran, A. Aboobaker, A.J. Varghese, P. Nancy, L. Ravindran, and S. Thomas, Review on sustainable flexible electronics: exploring the potential of chitosan, cellulose starch, silk fibroin and gelatin. Discover Polymers. (2025).2(1) 19.
53. Fu, K.K., Z. Wang, J. Dai, M. Carter, and L. Hu, Transient electronics: materials and devices. Chemistry of Materials. (2016).28(11) 3527-3539.
54. Han, W.B., J.H. Lee, J.W. Shin, and S.W. Hwang, Advanced materials and systems for biodegradable, transient electronics. Advanced Materials. (2020).32(51) 2002211.
55. Fan, X., B. Jiao, X. Zhou, W. Zhang, and Z. Ouyang, Miniaturization of Mass Spectrometry Systems: An Overview of Recent Advancements and a Perspective on Future Directions. Analytical Chemistry. (2025).97(17) 9111-9125.
56. Stephen, M., A. Nawaz, S.Y. Lee, P. Sonar, and W.L. Leong, Biodegradable materials for transient organic transistors. Advanced Functional Materials. (2023).33(6) 2208521.
57. Mirzajani, H., P. Zolfaghari, S. Akbari Nakhjavani, B.Y. Koca, M. Khodapanahandeh, and H. Urey, Transient implantable electronics for postsurgery preventive medicine. Advanced Functional Materials. (2025).35(3) 2413324.
58. Jamshidi, R., M. Taghavimehr, Y. Chen, N. Hashemi, and R. Montazami, Transient electronics as sustainable systems: from fundamentals to applications. Advanced Sustainable Systems. (2022).6(2) 2100057.
59. Nath, N., S. Chakroborty, D.P. Vishwakarma, G. Goga, A.S. Yadav, and R. Mohan, Recent advances in sustainable nature-based functional materials for biomedical sensor technologies. Environmental Science and Pollution Research. (2024).31(46) 57289-57313.
60. Kaushal, J.B., P. Raut, and S. Kumar, Organic electronics in biosensing: a promising frontier for medical and environmental applications. Biosensors. (2023).13(11) 976.
61. Mamun, M.A.A. and M.R. Yuce, Recent progress in nanomaterial enabled chemical sensors for wearable environmental monitoring applications. Advanced Functional Materials. (2020).30(51) 2005703.
62. Norrrahim, M.N.F., V.F. Knight, N.M. Nurazzi, M.A. Jenol, M.S.M. Misenan, N. Janudin, N.A.M. Kasim, M.F.A. Shukor, R.A. Ilyas, and M.R.M. Asyraf, The frontiers of functionalized nanocellulose-based composites and their application as chemical sensors. Polymers. (2022).14(20) 4461.
63. Panigrahi, P.K., B. Chandu, and N. Puvvada, Recent advances in nanostructured materials for application as gas sensors. ACS omega. (2024).9(3) 3092-3122.
64. Raghav, G., S. Moolayadukkam, N.R. Thomas, and G. George, Two-Dimensional Nanomaterials-Based Polymer Nanocomposites for Gas and Volatile Organic Compound Sensing. Two-Dimensional Nanomaterials-Based Polymer Nanocomposites: Processing, Properties and Applications. (2024)713-741.
65. Dutta, P. and G. Gupta, Environmental gas sensors based on electroactive hybrid organic–inorganic nanocomposites using nanostructured materials. Physical Chemistry Chemical Physics. (2022).24(47) 28680-28699.
66. Arman Kuzubasoglu, B., Recent studies on the humidity sensor: A mini review. ACS Applied Electronic Materials. (2022).4(10) 4797-4807.
67. Zhao, L., Y. Zhou, J. Zhang, H. Liang, X. Chen, and H. Tan, Natural polymer-based hydrogels: From polymer to biomedical applications. Pharmaceutics. (2023).15(10) 2514.
68. Kamoun, E.A., M. Elsabahy, A.M. Mohamed Elbadry, E.B. Abdelazim, A.A. Mohsen, M. A. Aleem, H. Gao, N.G. Eissa, I. Elghamry, and S.A. Salim, Recent progress of polymer-based biosensors for cancer diagnostic applications: natural versus synthetic polymers. ACS omega. (2025).10(9) 8816-8831.
69. Shaheen, A., N. Anwar, F. Chen, Y. Chan, H. Xie, and S.L. Lee, Materials interface engineering: impact of interfacial molecular orientation on organic electronic devices. Advanced Functional Materials. (2025).35(47) 2505173.
70. Zeng, H., Y. Xie, T. Liu, Z. Chu, E. Dempsey, and W. Jin, Conductive polymer nanocomposites: recent advances in the construction of electrochemical biosensors. Sensors & Diagnostics. (2024).3(2) 165-180.
71. Yang, J., Y. Chen, L. Zhao, J. Zhang, and H. Luo, Constructions and properties of physically cross-linked hydrogels based on natural polymers. Polymer Reviews. (2023).63(3) 574-612.
72. Asih, G.I.N., A.F. Rafryanto, S. Hartati, X. Jiang, A. Anggraini, A. Yudhowijoyo, and J. Jiang, Recent advances of polymer nanocomposites in emerging applications. Composite Functional Materials. (2025).1(1) 20250105.
73. Wang, M., Z. Deng, Y. Guo, and P. Xu, Engineering functional natural polymer-based nanocomposite hydrogels for wound healing. Nanoscale Advances. (2023).5(1) 27-45.
74. Shubhadarshinee, L., P. Mohapatra, S. Behera, B.R. Jali, P. Mohapatra, and A.K. Barick, Review on synthesis and characterization of metal nanoparticles doped carbon nanofillers based nanohybrids reinforced polyaniline nanocomposites. Polymer-Plastics Technology and Materials. (2024).63(8) 1011-1035.
75. Afzal, U., K. Wang, J. Liang, Z. Ma, Y. Wang, J. Wu, A. Fatima, L. Zhang, and Z. Wang, Chemical engineering for advanced flexible sensors: Novel carbon-metal oxide nanocomposites with superior multi-sensing behavior. Sensors and Actuators B: Chemical. (2025).431137449.
76. Wang, Y., S. Lu, W. He, S. Gong, Y. Zhang, X. Zhao, Y. Fu, and Z. Zhu, Modeling and characterization of the electrical conductivity on metal nanoparticles/carbon nanotube/polymer composites. Scientific Reports. (2022).12(1) 10448.

77. Wang, S., Z. Luo, J. Liang, J. Hu, N. Jiang, J. He, and Q. Li, Polymer nanocomposite dielectrics: understanding the matrix/particle interface. ACS nano. (2022).16(9) 13612-13656.
78. Khdier, H.M., K.A.F. Husham, W.M. Shali, and H.A. Al-Atabi. Interfacial effects on mechanical, thermal and electrical properties of polymer-based nanocomposites: a review. in Annales de Chimie. Science des Materiaux. 2024. International Information and Engineering Technology Association (IIETA).
79. El Itawi, H., S. Fadlallah, F. Allais, and P. Perré, Green assessment of polymer microparticles production processes: a critical review. Green Chemistry. (2022).24(11) 4237-4269.
80. Mondal, A., R.K. Singh, and A. Sinhamahapatra, Green and sustainable separation processes for environmental and chemical engineering, in Advances in separation sciences. 2025, Elsevier. p. 457-479.
81. Khan, M., M.F.A.D. Refati, M.M.R. Arup, M.A. Islam, and M.H. Mobarak, Conductive polymer-based electronics in additive manufacturing: Materials, processing, and applications. Advances in Polymer Technology. (2025).2025(1) 4234491.
82. Tan, P., H. Wang, F. Xiao, X. Lu, W. Shang, X. Deng, H. Song, Z. Xu, J. Cao, and T. Gan, Solution-processable, soft, self-adhesive, and conductive polymer composites for soft electronics. Nature communications. (2022).13(1) 358.

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Journal of Engineering, Science and Technological Trends (JESTT)

Vol. 3, Issue 2, July 2026
DOI: https://doi.org/10.64060/JESTT3i24

Article

Mitigating the Grey Sheep Problem in Collaborative Filtering via Hybrid Machine Learning Architectures

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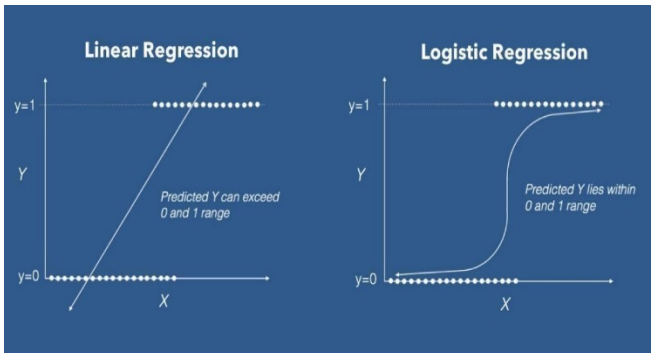
Received: 12 March 2026 / Revised: 23 June 2026 / Accepted: 02 July 2026 / Published online: 10 July 2026

ABSTRACT

In every nation, the major source of entertainment is movies. Worldwide, thousands of people watch movies to feel relaxed and escape from depression. The huge amount of data is an issue that is getting worse in online media. A System is created by using data mining techniques that helps to anticipate future trends, known as a prediction system or filtering system. In this system, the term grey sheep problem refers to users with unique preferences and interests that make it difficult to predict movies. In this research, Machine Learning models are used to identify the grey sheep problem and enhance movie search. A dataset of 15,538 movies was used and different attributes were selected that are publicly available on MovieLens. Then five main data mining techniques were used: Logistic Regression, Support Vector Machine, K-Nearest Neighbour, Naïve Bayes, and Decision Tree. All of the techniques gave their accuracy values, but out of all, Decision Tree gave the highest accuracy of 0.99% for movie prediction for grey sheep users.



Keywords: Machine Learning Algorithms; Movies; Algorithm; Movie Lens; Grey Sheep Users; Hybrid Learning

1. Introduction

The rapid expansion of the internet has brought about a massive amount of data online and it is becoming very hard to access the relevant information of a user in an efficient manner [1]. In order to deal with this problem, prediction systems (recommender systems) have come out as the necessary tools that offer customised recommendations depending on user preference, behaviour, and interactions. These systems are widely implemented in areas of e-commerce, entertainment and social media in order to improve user experience and interaction. There are three broadly used methods of operation of recommenders: content-based filtering (CBF), collaborative filtering (CF) and knowledge-based systems (KBS). Content-based algorithms are based on the characteristics of the item and the history of the users, whereas collaborative filtering is based on the similarities between the users or the items. Knowledge-based systems make use of explicit domain knowledge to produce recommendations. Hybrid methods that have used a combination of these methods in recent years have been proposed to enhance performance and accuracy [2]. The most important difficulty with recommender systems is the ability to deal with various kinds of users, especially grey sheep users. Unlike white sheep users (similar preferences) and black sheep users (minimal or no feedback), grey sheep users have unique and inconsistent preferences, and it is hard to find or create useful recommendations. Such users are usually difficult to manage by traditional recommendation methods because of the poor similarity

trends and sparsity of data. Data mining and machine learning have become popular in enhancing the accuracy of recommendations. Clustering, classification, and matrix factorisation are some of the methods that systems use to learn hidden patterns and user preferences based on large datasets. Nevertheless, current methods remain limited to predicting preferences of grey sheep users with reasonable accuracy, which is mostly caused by the scarcity of data and the absence of robust similarity measures. In order to overcome these shortcomings, this study proposes a content-based prediction system that is supplemented with machine learning to better represent the interests of the users and increase the accuracy of recommendations to the grey sheep users. The suggested solution will be built around a process of extracting important features and making use of user behaviour to create more credible and personalised movie recommendations. The primary aim of this research is to enhance the accuracy of predictions for users of the grey sheep and enhance the creation of more effective recommender systems in online media platforms. This section is also supported by some illustrative figures in order to understand the discussed concepts better. Figure 1 shows the category of users as white sheep, black sheep and grey sheep.

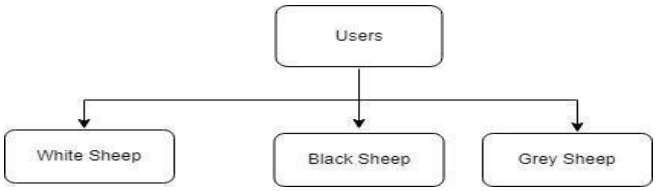


Figure 1: Types of Users.

Figures 2 and 3, as well as 4, show the nature of the recommender systems mechanism of collaborative and content-based filtering, respectively.

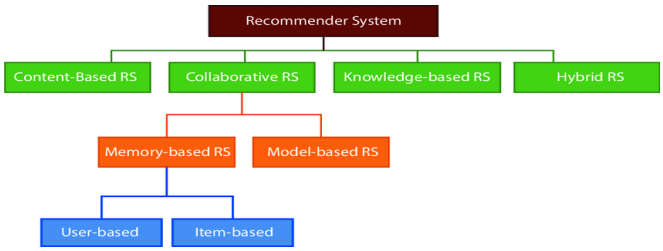


Figure 2: Types of Recommender Systems.

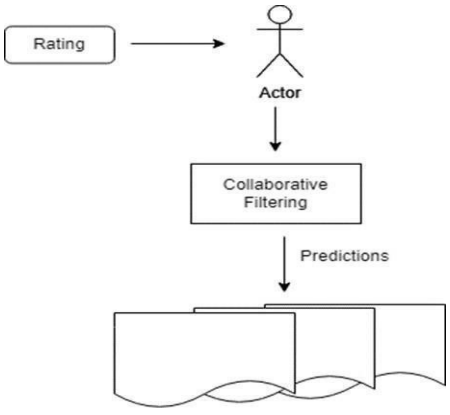


Figure 3: Collaborative Filtering-based Prediction System.

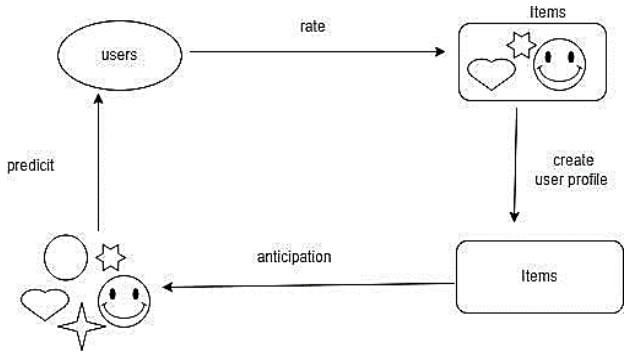


Figure 4: Content-based Filtering-based Prediction System.

Also, Figure 5 gives a descriptive analysis of the prediction systems. To help in understanding the machine learning background, Figure 6 depicts the general machine learning algorithm scheme, Figure 7 depicts the different types of regression and Figure 8 displays clustering methods. All these visuals enhance the clarity of the concepts and give a clear picture of the prediction systems and the machine learning methods explained in this section.

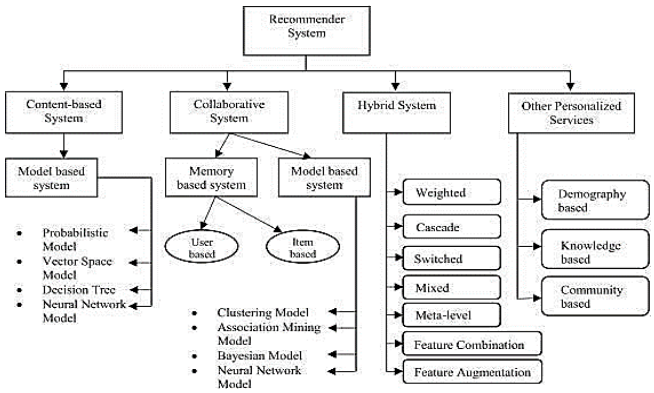


Figure 5: Detailed Classification of the Prediction System.

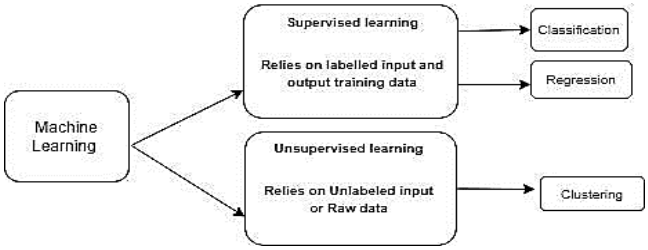


Figure 6: Machine Learning Algorithm Scheme.

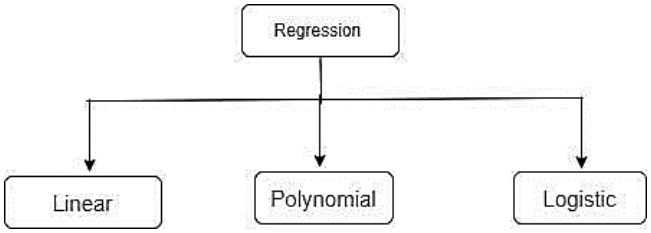


Figure 7: Types of Regression.

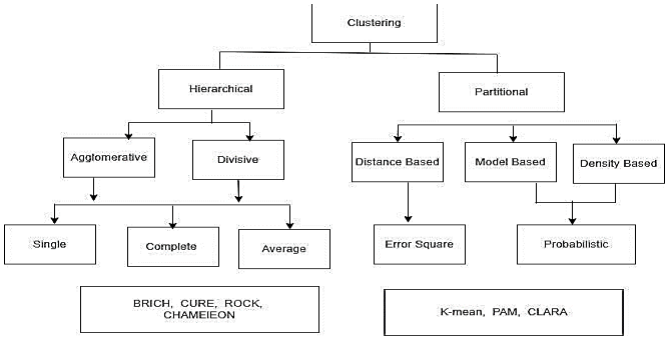


Figure 8: Clustering Types in Machine Learning.

2. Existing Study

The topic of movie recommendation systems has undergone a lot of research, but especially the identification and handling of grey sheep users, whose act of inconsistency or atypical preferences is a thorn in the prediction accuracy. Alabdul Rahman and Viktor [1] introduced the hybrid collaborative filtering model, the Grey-Sheep One-Class Recommendation (GSOR), which is a combination of one-class learning outlier detection and unsupervised learning with better prediction performance, particularly when they use Decision Tree classifiers. Likewise, Ziarani and Ravanmehr [2] have identified the need for novelty and diversity in recommendation systems, where the traditional data mining and machine learning algorithms can at times produce irrelevant predictions, and where contextual serendipity can help reduce the issue. In another strategy, Srivastava, Bala and Kumar [3] utilised psychographic models, the Big Five, Basic Human Values and Needs models to find grey sheep users in the e-commerce platform, and proved to be much more effective than the conventional rating-based methods, based on Amazon datasets. Other scholars were interested in improving clustering-based recommendation system techniques. Rashidi Khamforoosh and Sheikhahmadi [4] suggested the MKMeans++ algorithm, a combination of rating matrices and k-means clustering, demonstrating a better performance of MAE on MovieLens and FilmTrust datasets and the effect of more grey sheep users on prediction errors. On the same note, Jabbar, Mahamud, and Sagban [5] optimised the Ant Colony Optimisation to Clustering (M-ACOC), and it outperformed intra-distance and F-measure in six UCI datasets. There was also a discussion on trust-aware systems, where Gohari, Aliee and Haghighi [6] proposed Significance-Based Trust-Aware Recommendation (SBTAR), which is able to adapt to the changing user preferences using demographic settings and meta-heuristic optimisation, which is more accurate and efficient than current systems. Shokeen and Rana [7] also showed the incorporation of social network functionality in recommender systems, and developed social recommender systems which improve the quality of recommendations and overcome the shortcomings of traditional methods.Evolutionary algorithms and hybrid algorithms have also been promising. Mohammadpour et al. [8] used Genetic Algorithms with Gravitational Emulation Local Search to maximise clustering in collaborative filtering systems, which enhanced predictive performance on MovieLens and FilmTrust data sets. Ahuja, Solanki, and Nayyar [9] applied k-Means and k-NN clustering to movie recommendation, showing lower values of RMSE and fewer clusters on MovieLens. A hybrid collaborative filtering and content-based approach was suggested by Jindal, Agarwal, and Sardana [10] to detect grey sheep users and the authors obtained improved accuracy in their prediction and reduced MAE by 4.62 and 0.7757, respectively. Further studies on collaborative filtering methods were discussed by Ayub et al. [11], who pointed out weaknesses of similarity metrics like Jaccard on person-specific forecasting. To solve the cold-start problem, Gope and Jain [12] classified the solutions to be explicitly or implicitly implemented and proposed combining these methods to get improved recommendations.The problems of the accuracy of prediction and the overload of information have been well-known. Khusro, Ali and Ullah [13] have highlighted that quality prediction systems are required to present the relevant information efficiently and found research opportunities to overcome the current limitations. Models based on trust, e.g. TrustSVD, and Bayesian similarity measures as suggested by Guo, Zhang, and Yorke-Smith [14],[15] enhance performance by combining various sources of information and alleviating sparsity in data. Ghazanfar and Pruegel-Bennett [16],[17] also investigated improvements to K-Means clustering in identifying grey sheep, such as centroid initialization and distance matrix adjustments and Tang et al. [18] applied bio-inspired optimization algorithms, such as C-Ant, Bat, Cuckoo and Wolf Search, to clustering to achieve better convergence and fitness on a variety of datasets Qiu et al. [19] proposed a twofold bootstrapping propagation based opinion mining, which realized notable improvements on precision but Shan and Banerjee [20] experimented with probabilistic matrix factorization models using side information and bias correction to improve prediction accuracy. Nguyen et al. [21] also proposed hybrid recommendation approaches which used fuzzy reasoning and demographic data and Burke [22] performed a comprehensive analysis of hybrid recommender systems which used collaborative filtering as well as knowledge-based methods to overcome the cold-start problem. In general, the literature reveals that collaborative, content-based, clustering, trust-based, evolutionary and hybrid methods of movie recommendation systems have been greatly utilised. Although major strides have been taken to recognise and reduce the impact of the grey sheep users, there are still issues of advancing the accuracy, coverage and efficiency of prediction. The combination of psychographic modelling, trust-awareness, hybrid optimisation and social network capabilities seems to be a good idea to improve the results of recommendations and overcome the weaknesses of current systems.

Deep learning, matrix factorisation, ensemble learning and hybrid recommendation models have been increasingly applied in recent years to recommender systems research. While these methods have shown good results, the current study concentrates on the effectiveness of classical supervised machine learning methods for grey sheep user identification, thus offering a good baseline for further comparison.

3. Methodology

Grey sheep users can be defined as persons with unique tastes whose interests are not easily predictable in a system. Their preferences are unusual; thus, it is challenging to determine connections with other users even though they are proactive in offering feedback and expressing opinions. The chapter describes the approach planned to improve the search for movies among the grey sheep users by the use of machine learning. The suggested research will integrate various machine learning algorithms and a tailored movie dataset to enhance the quality of prediction and recommendations. The methodology is a complete procedure of the research which involves the proposed computational model, dataset structure, tools and technologies, evaluation criteria and the machine learning methods that are applied to classify data. The suggested computational model of computation, as shown in Figure 9, Research Proposed Method, exploits a dataset that was obtained from MovieLens (2019) and includes various attributes. Data preprocessing is used to remove the features that are directly associated with the preferences of the user's movies, which allows identifying grey sheep users correctly. The process of data collection is organised to collect and assess variables in the publicly available

dataset, which is converted into a CSV to be compatible with machine learning algorithms. Data preprocessing is used to clean, integrate, transform and sample raw datasets, which usually have inconsistencies, noise, or missing values. Cleaning will eliminate duplications, outliers and noisy entries, whereas integration will consolidate various data sources, and transformation will normalise and discretise data to an appropriate format to be analysed. Sampling minimises the computational cost by choosing representative subsets and overfitting is reduced to ensure that the models are not learning noise instead of generalizable patterns, as shown in Figure 10: Data Overfitting.

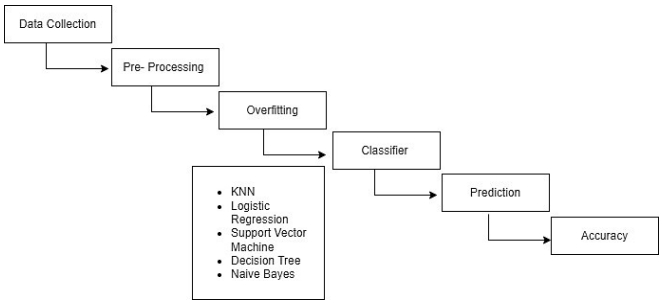


Figure 9: Research Proposed Method.

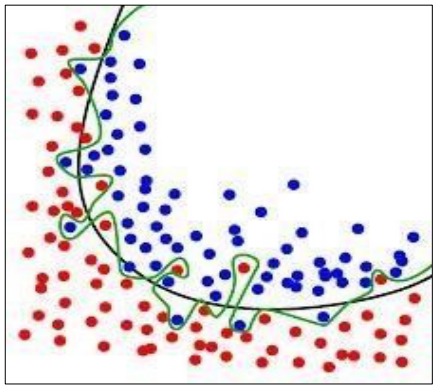


Figure 10: Data Overfitting.

The process of data mining incorporates several supervised learning methods, such as Logistic Regression (LR), K-Nearest Neighbour (KNN), Naive Bayes (NB), Support Vector Machine (SVM), Decision Tree (DT), Random Forest (RF) and Gradient Boosting (GB). All the algorithms are trained and tested with various parameters to establish their predictive qualities, especially for grey sheep users. The last dataset format presented in Table 1: Final Dataset Structure incorporates the features of Movie ID, Rating, Views, Title and user Labels (grey or white), which are essential to supervised learning and model testing.

A rule-based labelling strategy was used to identify grey sheep users. A movie was considered a grey sheep user if it had fewer than 20,000 views and had a rating of 3 or higher. These films suggest users who are different from the mainstream since they give positive ratings to relatively obscure material. The users that do not meet this criterion were classified as white sheep users.

All of the proposed framework is based on a hybrid machine learning structure with several processing stages in the same recommendation framework. The architecture comprises data preprocessing for datasets, feature extraction, rule-based grey sheep labelling, supervised machine learning-based classification and recommendation-based analysis. In this work, the hybrid architecture is not an ensemble classifier, but rather the combination of the concepts of the recommendation system with different machine learning processing steps. In particular, the framework integrates two stages of data pre-processing, feature extraction, rule-based grey sheep labelling and supervised machine learning grey sheep classification in one workflow. The proposed hybrid architecture is not a combination of more than one classifier as an ensemble model, but the combination of recommendation system methodology and machine learning techniques.

Table 1:
Final Dataset Structure

Attributes	Meaning	Example
Movie Id	Movie unique ID	3176
Rating	Rating is given by the user	5
Views	How many users view	7049,957
Title	Movie title	Wild Horses (Caballossalvajes) (1995)
Labels	Label users' type	Grey or white

The training models require labelled datasets, which allow algorithms to identify patterns and make correct inferences, and the result can be observed in Figure 11: Output of Label Data. The notebook is based on Python, which is the main program to be used to run and analyse.

	A	B	C	D	E
	movieId	rating	views	label	Label
	1	5	74	grey	grey
	3	5	198	grey	grey
	4	5	219	grey	grey
	25	5	223	grey	grey
	27	5	330	grey	grey
	9	5	431	grey	grey
	20	5	479.48	grey	grey
	24	5	479.65	grey	grey
	23	5	479.69	grey	grey
	19	5	480.05	grey	grey
	34	5	630.11	grey	grey
	38	5	814.8	grey	grey
	42	5	999.49	grey	grey
	49	5	1322.7	grey	grey
	57	5	1692.1	grey	grey
	58	5	1738.2	grey	grey
	70	5	2292.3	grey	grey
	73	5	2430.8	grey	grey
	77	5	2615.5	grey	grey
	80	5	2754	grey	grey
	81	5	2800.2	grey	grey
	86	5	3031	grey	grey
	90	5	3215.7	grey	grey
	103	5	3769.8	grey	grey
	104	5	3815.9	grey	grey
	105	5	3862.1	grey	grey
	108	5	4000.6	grey	grey
	110	5	4093	grey	grey
	115	5	4323.8	grey	grey
	116	5	4370	grey	grey

Figure 11: Output of Label Data.

Machine learning algorithms because it is cross-platform and has extensive data analysis libraries. Parameters are set to assess model performance, including ways to identify overfitting or underfitting. The data is divided into training and testing sets, usually in an 80:20 proportion in order to make sure that models can be used effectively even on unseen data. To compute the results of classification, the confusion matrix is used and in the context of classification results, the accuracy, precision and recall are mathematically defined by Equation (1), Equation (2) and Equation (3), respectively, which give quantitative measures of the model performance.

$$\text{Accuracy} = \frac{TN + TP}{(TN + FP + TP + FN)} \quad (1)$$

$$\text{recision} = \frac{TP}{(TP + FP)} \quad (2)$$

$$\text{Recall} = \frac{TP}{(TP+FN)} \quad (3)$$

The research applies seven machine learning methods to the prediction of grey sheep users. Logistic Regression (LR) models are relations between the dependent and independent variables and their mathematical model is presented in Equation (3) and the comparison of the linear and logistic regression is shown in Figure 12: Linear Regression Vs Logistic Regression Graph.

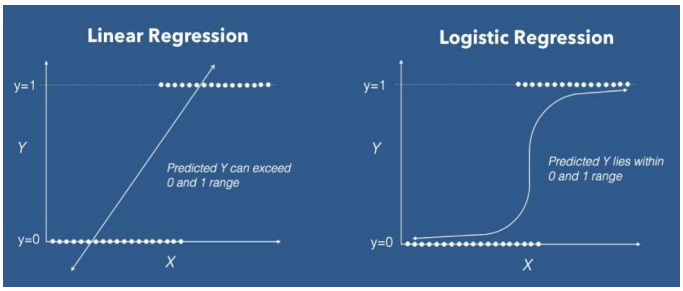


Figure 12: Linear Regression Vs Logistic Regression Graph.

Support Vector Machine (SVM) algorithms form hyperplanes to classify classes both in linear and non-linear space, as shown in Figure 13: SVM Classification of Data and Figure 14: SVM Classification of Non-Linear Data. Decision Trees (DT):

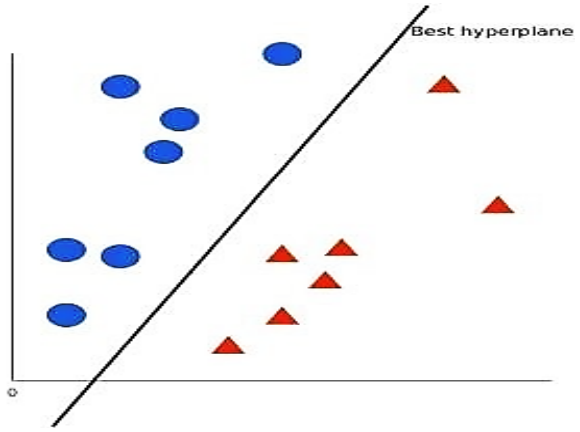


Figure 13: SVM Classification of Data.

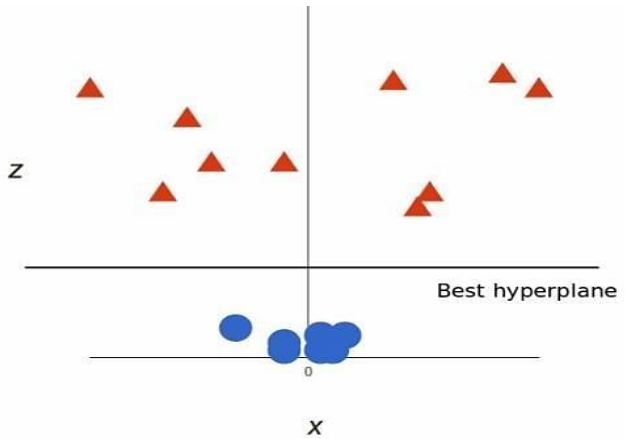


Figure 14: SVM Classification of Non-Linear Data.

This is based on hierarchical structures to group data according to information gain and entropy, and the classification output is provided in Figure 15:

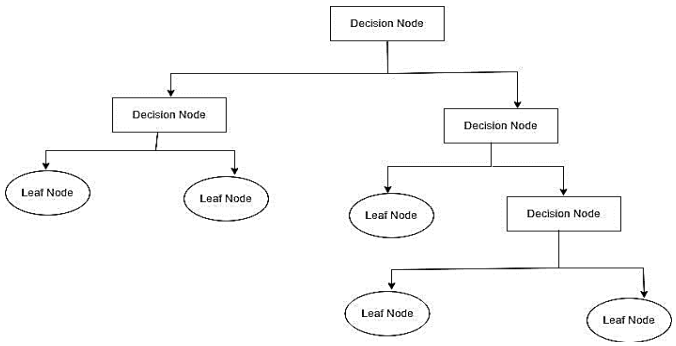


Figure 15: Classification of Decision Tree.

Classification of Decision Tree. K-Nearest Neighbour (KNN) is a classifier that allocates a label based on the proximity of the neighbouring points, which is computed with the help of Euclidean distance (Figure 16: Calculation of Euclidean Distance) and illustrated in Figure 17: K-Nearest Neighbour Showing Nearest Neighbour.

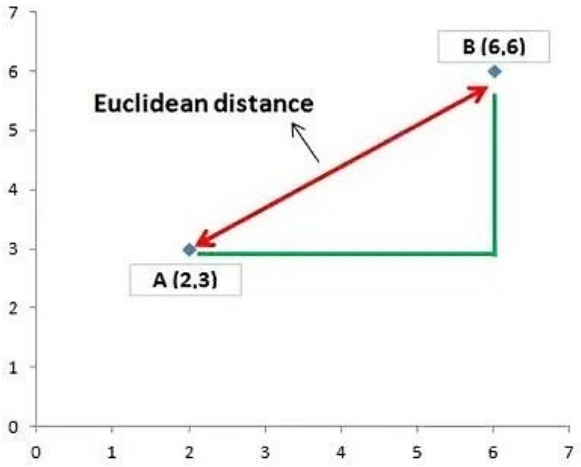


Figure 16: Calculation of Euclidean Distance.

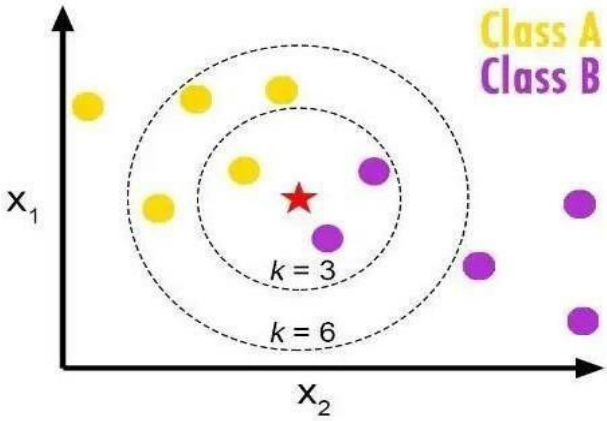


Figure 17: K-Nearest Neighbour Showing Nearest Neighbour.

Naive Bayes (NB) classifiers are classifiers that assume feature independence to scale in terms of efficiency and scalability (Figure 18: Naïve Bayes Classifier).

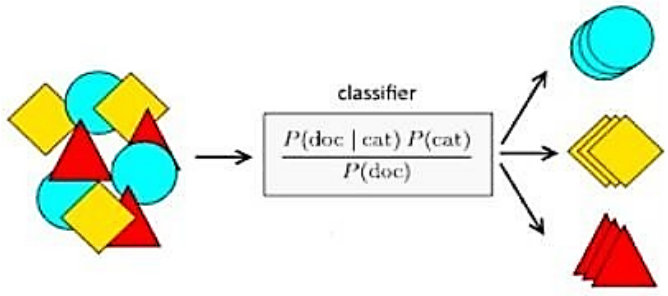


Figure 18: Naïve Bayes Classifier.

Random Forests (RF) combine the decisions of several Decision Trees, taking advantage of bootstrap sampling and randomness of features and the model operation is shown in Figure 19: Random Forest Classifier.

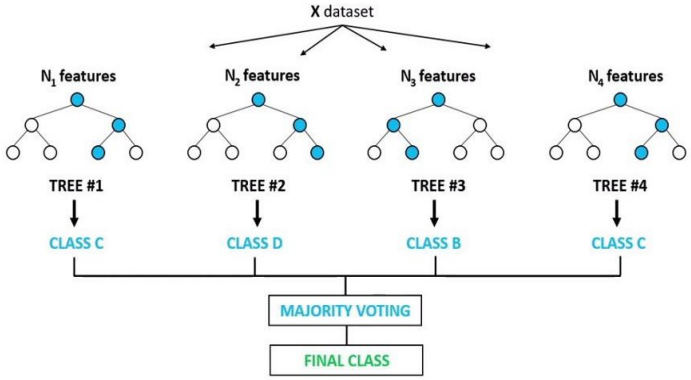


Figure 19: Random Forest Classifier.

Gradient Boosting (GB) models are optimised sequentially to minimise bias and variance, and the workflow is illustrated in Figure 20: Working Flow of Gradient Boosting Classifier.

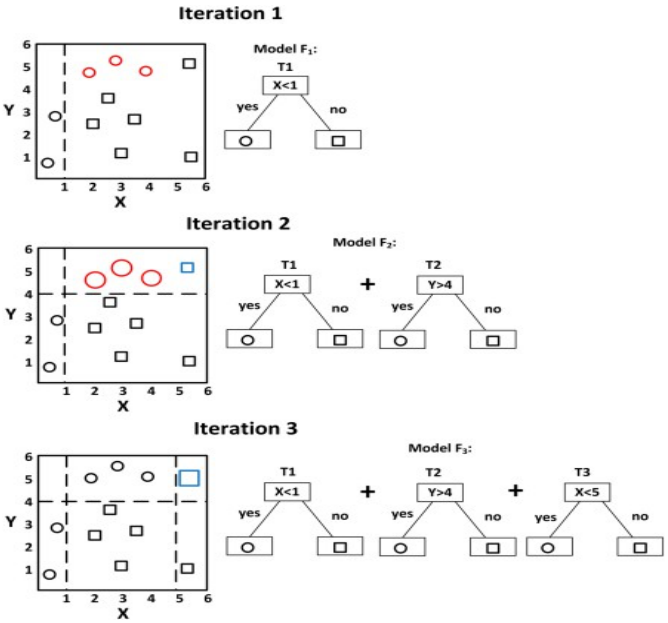


Figure 20: Working Flow of Gradient Boosting Classifier.

All these algorithms are used to identify grey sheep users using various attributes so that the predictive accuracy can be maximised and overcome the problem of overfitting or data sparsity. Overall, the chapter outlines the systematic research process in prediction and classification of grey sheep users on the basis of machine learning. It involves extensive data preprocessing, proper labelling, and using various supervised learning algorithms. Evaluation parameters such as accuracy, precision, recall, and confusion matrices give quantitative information about the model performance, which makes the proposed methods robust and effective to identify unique user preferences.

4. Results and Discussion

In this chapter, the experimental assessment and a thorough discussion of the suggested method of detecting the users of grey sheep in movie recommendation systems are provided. The research uses the MovieLens dataset comprising 1,002,009 ratings given by 6,040 users on almost 3,900 films and longer data of 15,512 films with ratings and the number of views. The data were preprocessed and classified into grey sheep users and white sheep users based on an IF condition whereby users with high ratings and fewer views were classified as grey sheep users and 7,708 white sheep users, respectively, as shown in Figure 21: Distribution of Users in the CSV Dataset. The dataset was separated into 80% training and 20% testing, with X being the columns (except the label) and Y being the label column. Data was processed through the Pandas library with the labelled CSV dataset and model training and testing were done after splitting the data.

$$\text{Grey Sheep} = \begin{cases} 1, \text{ if Rating} \geq 3 \text{ and Views} < 20{,}000 \\ 0, \text{ Otherwise} \end{cases}$$

To achieve consistency across all classifiers, the present study used the commonly used train-test evaluation protocol of 80:20. Another approach to providing robustness analysis is provided by k-fold cross-validation, but this was not investigated in the present study and has been recognised as a key area for future research.

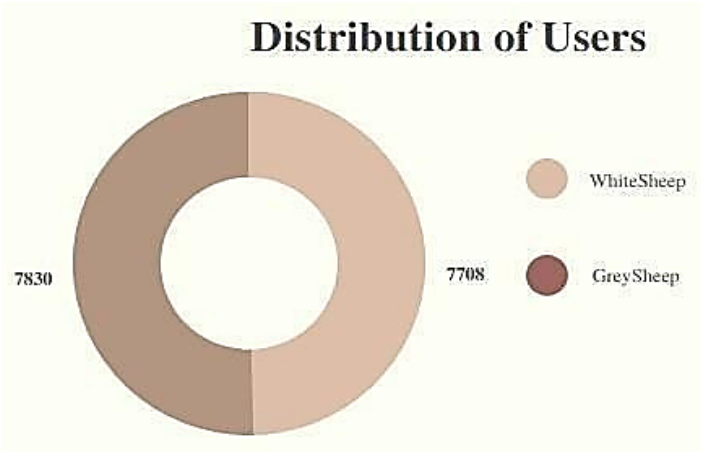


Figure 21: Distribution of Users in the CSV Dataset.

To assess the performance of the proposed method, several machine learning algorithms were used, such as Naive Bayes, K-Nearest Neighbour (K-NN), Logistic Regression (LR), Support Vector Machine (SVM) and Decision Tree (DT). The accuracy, F1-score, precision and recall were used to measure the performance of these algorithms. The results of the precision evaluation are given in the Figure 22: Evaluation of Precision Along K-NN, Figure 23: Evaluation of Precision Along with SVM, Figure 24: Evaluation of Precision Along LR Similarly, F1-score evaluations are shown in Figure 25: Evaluation of F1 Along with Naïve Bayes, Figure 26: Evaluation of F1 Along with SVM, Figure 27: Evaluation of F1 Along K-NN, demonstrating the comparative performance of each algorithm across different evaluation metrics.

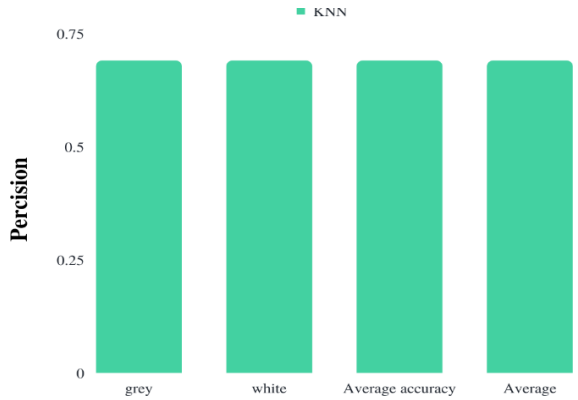


Figure 22: Evaluation of Precision Along LR.

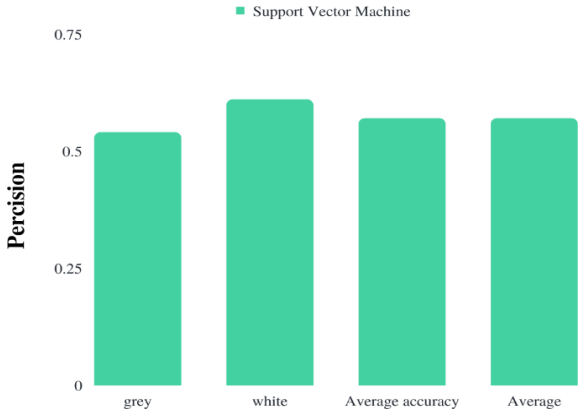


Figure 23: Evaluation of Precision Along K-NN.

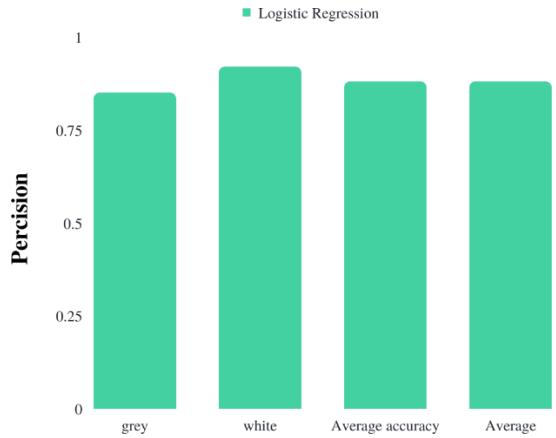


Figure 24: Evaluation of Precision Along LR.

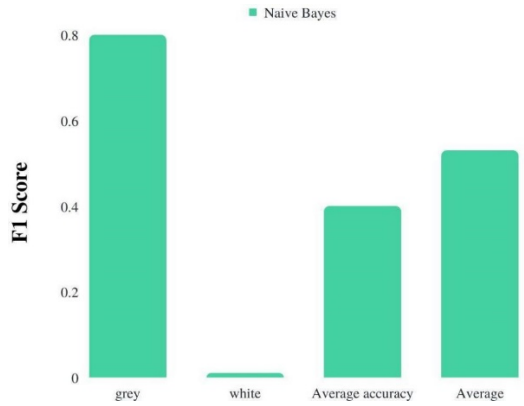


Figure 25: Evaluation of F1 Along with Naïve Bayes.

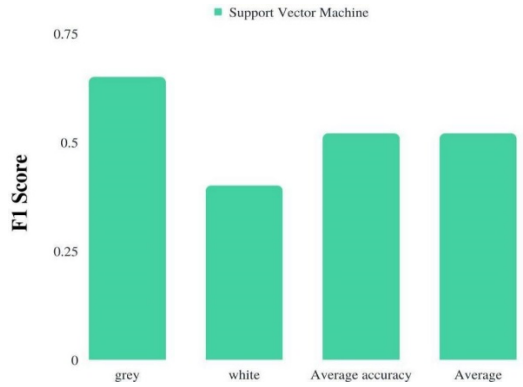


Figure 26: Evaluation of F1 Along with SVM.

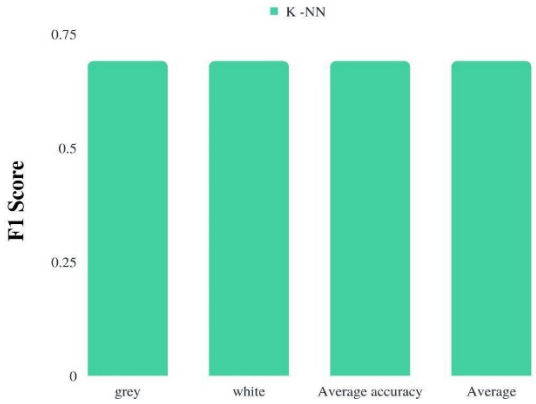


Figure 27: Evaluation of F1 Along with K-NN.

The standard formula used to calculate accuracy is Accuracy = (TN + TP) / (TN + FP + TP + FN) and the results of the comparisons are summarised in Table 2: Accuracy Comparison and graphically presented in Figure 28: Gained Accuracy After Comparing Different Algorithms. These findings have shown that the Decision Tree algorithm was most accurate at 0.99 with perfect recall, precision and F1-score and next was the Logistic Regression at 0.88 and then SVM. Moreover, the efficiency of the given method was also confirmed by the comparison with the existing methods, which are presented in Table 3: Comparison Table and Figure 29 Comparison Graph with Previously Used Algorithms, where the given technique was more efficient in terms of accuracy than MKMeans++, SFLA, PCC and Collaborative Filtering methods.

Table 2:
Accuracy Comparison

Algorithm	Accuracy	Recall	F1 Score	Precision
NB	0.66	0.67	1.00	0.80
K-NN	0.69	0.69	0.70	0.69
LR	0.88	0.85	0.93	0.89
SVM	0.55	0.54	0.82	0.65
DT	0.99	1.0	1.0	1.0

The performance reported is measured on experiments carried out under a uniform experimental setup with the MovieLens dataset. The Decision Tree classifier outperformed the other classifiers because the features used for this classification were selected (Movie ID, Rating, Views, Title and Labels) and the labelling strategy used in this study was well-defined. The results reported are valid only for the data set used and are not representative of all data sets for recommender systems.

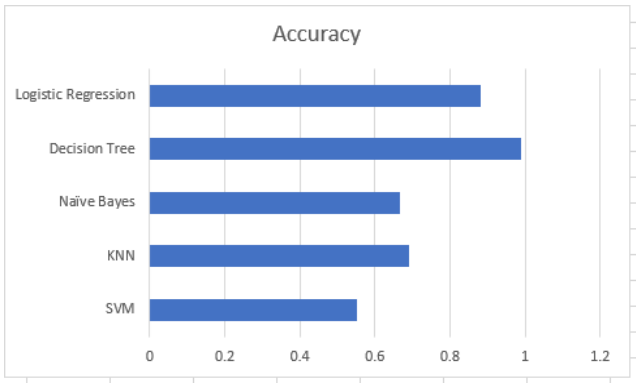


Figure 28: Gained Accuracy After Comparing Different Algorithms.

Table 3:
Comparison Table

Sr. No.	Author	Method	Accuracy
1	(Rashidi, Khamforoosh, & Sheikhahmadi, 2022)	MKMeans++, FirefyMkMeans++	68%
2	(Gohari, Aliee, & Haghighi, 2020)	Shuffled Frog Leaping Algorithm (SFLA), Significance-Based Trust-Aware Recommendation (SBTA)	60%
3	(Reddy, Kanmani, & Surendiran, 2020)	Pearson correlation coefficient (PCC)	48%
4	(Gras, Brun, & Boyer, 2016)	Collaborative Filtering	90%
5	(Proposed Method)	Decision Tree, Logistic Regression, K-Nearest Neighbour, Naïve Bayes, Support Vector Machine	99% 88% 69% 66% 55%

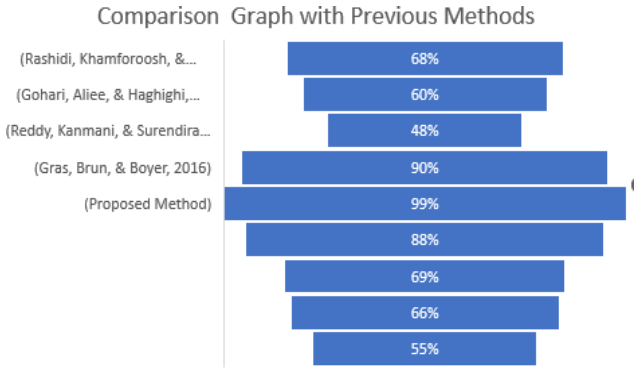


Figure 29: Comparison Graph with Previously Used Algorithms.

Another issue that the study deals with is imbalanced datasets, where grey sheep users are the minority group, by using both machine learning, anomaly detection, and one-class classification methods to enhance the predictive accuracy. Also, sample profiles of grey sheep users can be found in Table 4: Profile Sample of Grey Sheep Users with a focus on such attributes as movie ID, title, year, awards and IMDB ratings. Generally, the results show that the proposed intelligent recommender system can be used as an effective tool for improving the accuracy of the predictions and also in identifying grey sheep users, thus making the proposed system a great tool compared to the current system.

This study aimed to evaluate the performance of machine learning classifiers against popular classifiers and use widely accepted evaluation metrics such as accuracy, precision, recall and F1-score. Other measures like ROC-AUC and statistical significance testing are recognised as useful additions and have been identified as future work.

Table 4:
Profile Sample of Grey Sheep User

Movie Id	Title	Year	Awards	IMDB.com
73,023	Crazy Heart	1996	12 Gener: Drama-Romance	82,278
74,545	Ghost Writer	2010	23 Gener: Drama - Mystery Thriller	153,234
78,574	Ghost Writer	2010	29 Gener: Drama-Mystery Thriller	132,434
81,158	Restrepo	2010	10 Genre: Documentry-war	21,606
81,788	The Next Three Days	2010	0 Gener: Drama-crime	176,901
82,667	I Saw The Devil	2010	15 Gener: Crime- thril	103,699

5. Conclusion and Future Work

The study on the users of grey sheep is summarised, and the unique preferences used by these users are described to ensure that proper prediction is difficult to achieve in the recommendation systems. The study emphasises the role of predictive systems in aiding decision-making in a wide range of areas and introduces a unique approach aimed at enhancing the movie recommendations to such users. It is possible to apply and evaluate multiple machine learning algorithms and the best accuracy of 0.99 with perfect recall and F1-score was achieved on Decision Tree, whereas Logistic Regression (0.88), K-Nearest Neighbour (0.69) and Support Vector (0.55) had lower accuracy. The dataset used in the study is the publicly available MovieLens dataset, where data preprocessing, feature selection and implementation were conducted in Python within a Jupyter Notebook environment. The results indicate that the suggested method has a significant positive effect on prediction accuracy and Decision Tree is the most successful method to identify grey sheep users. Additionally, the study proposes future studies, such as incorporating information on trust and distrust, adding contextual variables (of time, place and user emotions) and testing the methodology with other data sets to further validate and compare the results. Further testing of the proposed framework will also be carried out in future using multiple benchmark datasets to assess the robustness of the framework through k-fold cross-validation.

Declaration

AI Disclosure: N/A

Availability of Data and Materials: All data is provided in the paper.

Competing Interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Consent to Publish: The authors agree to publish the version of the manuscript in this journal.

Ethical Issues: There are no ethical issues.

Funding Statement: N/A.

References

1. Aamodt, A., & Plaza, E. (1994). Case-based reasoning: Basic issues, approaches and methods. AI Communications, 7(1), 39-59.
2. Ahirwadkar, B., & Deshmukh, S. (2019). Recommender systems using deep neural networks. International Journal of Innovative Technology and Exploring Engineering, 8(12), 4838-4842.
3. Ahuja, R., Solanki, A., & Nayyar, A. (2019). Movie recommender system based on KMeansclustering and KNearest Neighbor. In 9th International Conference on Cloud Computing, Data Science & Engineering (Confluence), 10th - 11th January, India, (pp. 263-268). IEEE.
4. Ajit, P. (2016). Machine learning algorithms for prediction of employee turnover rate in organizations. Algorithms, 4(5), 5-12.
5. Alabdulrahman, R., & Viktor, H. (2021). Meeting different needs: One-class machine learning for grey sheep users recommender systems. Expert Systems with Applications, 166(7), 114-061.
6. Anonymous (2014) MovieLens, Avilable online at, courses, Group Lens (https://grouplens.org/datasets/movielens/), visited on 04-JAN-2023.
7. Ayub, M., Ghazanfar, M. A., Maqsood, M., & Saleem, A. (2018). A jaccard base similarity measure to improve performance of CF based recommender systems. I n International Conference on the Information Networking (ICOIN), 10th - 12th January, Thailand, (pp. 1-6). IEEE.
8. Aziz, N., Akhir, E. A. P., Aziz, I. A., Jaafar, J., Hasan, M. H., & Abas, A. N. C. (2020). Gradient boosting algorithms in development of artificial intelligence systems for monitoring and prediction. International Conference on Computational Intelligence (ICCI), 08th - 09th October, Malaysia, (pp. 11- 16). IEEE.
9. Balabanović, M., & Shoham, Y. (1997). Fab: content-based, collaborative recommendation. Communications of the ACM, 40(3), 66-72.
10. Billsus, D., & Pazzani, M. J. (2000). User modeling for adaptive news access. User Modeling and User-Adapted Interaction, 10(2), 147-180.
11. Bishop, C. M., & Nasrabadi, N. M. (2006). Pattern recognition and machine learning Springer, 4(5), 738.
12. Bobadilla, J., Ortega, F., Hernando, A., & Gutiérrez, A. (2013). Recommender systems survey. Knowledge-Based Systems, 46(5), 109-132.
13. Boser, B. E., Guyon, I. M., & Vapnik, V. N. (1992). Training an optimal margin classifier: A support vector machine. In Fifth Annual Workshop on Computational Learning Theory, 66(1), 144-152.
14. Boutilier, C., Brafman, R. I., Hoos, H. H., & Poole, D. (1999). Reasoning With Conditional Ceteris Paribus Preference Statements. UAI, 99(2), 71-80.
15. Breese, J. S., Heckerman, D., & Kadie, C. (2013). Collaborative filtering for imputation. ArXiv Preprint ArXiv:10(8),1301-7363.
16. Breiman, L. (2001). Random forests. Machine learning, 45, 5-32.
17. Burke, R. (2002). Hybrid recommender systems: Survey and experiments. Burke, R. (2007). Hybrid web recommender systems. The adaptive web, 77(1), 377
18. Elsalamony, H. A. (2014). Data mining techniques for bank direct marketing. International Journal of Computer Applications, 85(7), 12-22.
19. Felfernig, A. and Burke, R. (2008). Technology and research challenges of constraint-based recommender systems. In 10th International Conference on Electronic Commerce,67(8), 19th August, Austria, (pp. 1-10).
20. Adomavicius, G., & Tuzhilin, A. (2005). The next generation of recommender systems: A survey of the state-of-the-art and future directions. IEEE Transactions on knowledge and Data Engineering, 17(6), 734-749.

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Journal of Engineering, Science and Technological Trends (JESTT)

Vol. 3, Issue 2, July 2026
DOI: https://doi.org/10.64060/JESTT3i25

Review

Role of Pectinases and Carbohydrate-Degrading Enzymes in Biosensing Applications

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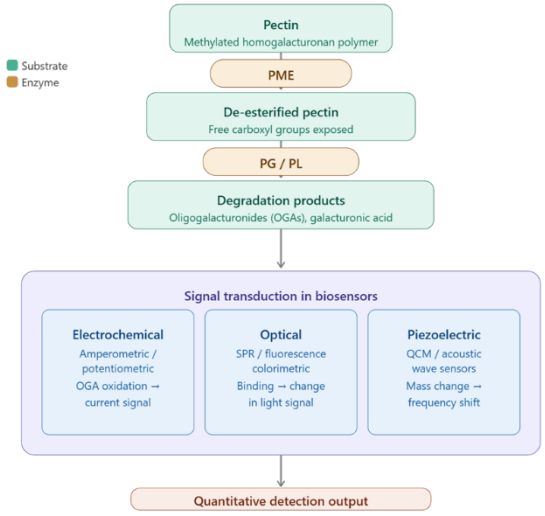
Received: 23 April 2026 / Revised: 19 June 2026 / Accepted: 07 July 2026 / Published online: 10 July 2026

ABSTRACT

Enzyme-based biosensors have emerged as powerful analytical platforms for transforming specific biochemical interactions into measurable signals, enabling rapid, sensitive, and selective monitoring across healthcare, food safety, environmental analysis, and industrial biotechnology. However, current enzyme biosensing research has predominantly focused on oxidoreductases, while carbohydrate-active enzymes (CAZymes) remain comparatively underexplored despite their exceptional substrate specificity and catalytic diversity. This review provides a comprehensive overview of carbohydrate-degrading enzyme-based biosensors, highlighting their fundamental mechanisms, sensing strategies, and future technological opportunities. Particular emphasis is placed on pectinases, including pectin methylesterase, polygalacturonase, and pectin lyase, which offer unique capabilities for detecting pectin degradation, plant physiological changes, food quality deterioration, and environmental processes. The catalytic principles of these enzymes, their production approaches, and their integration with electrochemical, optical, piezoelectric, and colourimetric transduction systems are systematically discussed. Furthermore, advanced immobilisation approaches involving nanomaterials, microfluidic architectures, and hybrid enzyme–nanozyme systems are examined to address challenges associated with enzyme instability, sensitivity, matrix interference, and reproducibility. Emerging concepts including artificial intelligence-assisted biosensing, wearable sensing platforms, multiplex detection, and sustainable biodegradable sensor designs are also explored as pathways toward next-generation intelligent biosensors. Despite significant progress, practical translation remains limited by substrate variability, large-scale manufacturing challenges, and insufficient standardisation. Future advances in enzyme engineering, smart data analysis, and integrated sensing technologies are expected to establish robust, portable, and environmentally sustainable biosensing platforms. This review provides critical insights into the development of advanced CAZyme-based biosensors and their potential role in shaping future intelligent analytical systems.



Keywords: Biosensing; Carbohydrate-Active Enzymes; Enzyme Engineering; Nanomaterials; Pectinase

1. Introduction

The recent advancements in sensors depend greatly on effective interaction between humans and machines, with biosensors being very important in this situation as they are used in transforming biochemical information into statistical data related to biological health, environment and food [1],[2]. However, the use of pectinase and other carbohydrate-degrading enzymes in practical application continues to face problems like insufficient enzyme stability, insufficient sensitivity, loss through

the matrix, and repeatability in actual samples [3],[4]. Therefore, it is important to design efficient biosensors that take into account pectin and other carbohydrate-sensitive enzymes [5],[6]. Biosensors refer to devices that utilise biological reactions to generate an electric signal [7]. These reactions are normally brought about by the use of bioreceptors that are mainly enzymes, antibodies, or nucleic acids together with transducers [8],[9]. Biosensors have a wide range of applications in different fields such as food safety, health care, and the environment, all owing to their specificities and sensitivities [10]. Common examples of biosensors include biosensors for blood glucose monitoring and paper-based biosensors that are inexpensive and can be used portably to detect biomarkers in food, medical samples, and environmental samples [11]. Biosensors are generally constructed using biological components such as antibodies, DNA/RNA, enzymes, and receptors combined with supportive matrices including hydrogels, polymers, nanoparticles, and conductive surfaces to provide a medium for signal generation and stability [12],[13]. In addition, other materials such as biopolymers (e.g., pectin), carbon nanotubes, conducting polymers, graphene, and metallic nanoparticles are often used in immobilising matrices and transducers of biosensors [14],[15]. In order to achieve sustainability, enzyme biosensors are designed from biodegradable and renewable sources in order to mitigate any harm to the environment without compromising the performance of these biosensors, which is characterised by high sensitivity and selectivity in detecting the target analyte [16],[17]. In this regard, enzymes play a significant role in acting as specific catalysts in biosensors and thus the ability to detect analytes such as glucose and contaminants as well as markers in biological studies [18]. The use of environmentally friendly materials such as cellulose and other biopolymers facilitates the design of cost-effective, disposable, and environmentally sustainable biosensors [19],[20].

The first biosensor was introduced in 1962 by Leland C. Clark Jr. and Champ Lyons, who invented an amperometric oxygen electrode based on the enzyme glucose oxidase for measuring glucose concentrations in the blood [21]. This development became the basis of contemporary glucose monitoring and opened the way for developing enzyme biosensors. In 1977, the term "biosensor" emerged when researchers invented the selective arginine electrode using biological components as recognition elements [22]. The first enzyme biosensor functioned by immobilising enzyme glucose oxidase at an electrode [23]. As glucose was being transformed in the presence of glucose oxidase, hydrogen peroxide appeared, whose amount proportionally depended on glucose concentration [24]. A simple electrochemical measurement system helped make biosensors very convenient in medical diagnostics, including monitoring diabetes [25]. Nowadays, glucose biosensors are still one of the main types of enzyme biosensors, and the two enzymes used for glucose determination are glucose oxidase (GOx) and glucose dehydrogenase (GDH) [26]. Recently, there has been significant interest in developing green and sustainable biosensors [19]. Designing sustainable biosensors involves biodegradable and environmentally friendly materials such as paper, cellulose, bioplastics and hydrogels [27]. The use of such materials helps not only decrease the waste but also recycle biosensors [28]. Life cycle assessment can be applied to evaluate the sustainability that consists of the use of raw materials, energy, and other parameters of biosensor life cycles, including their durability and possibility of recycling [22],[29]. There are many examples of biosensors based on using recent enzymes in order to improve performance and detection characteristics [30]. Examples of enzymes used in biosensors include horseradish peroxidase, lactate dehydrogenase, phenylalanine hydroxylase, and enzymes for determining uric acid and genetic diseases [7]. Biosensors with such enzymes are characterised by higher sensitivity, specificity, and detection limit in clinical, environmental applications and others [22],[31]. Nowadays, biosensors attract scientists representing various scientific areas because of multiple applications in medicine, environmental monitoring, the food industry, and public health

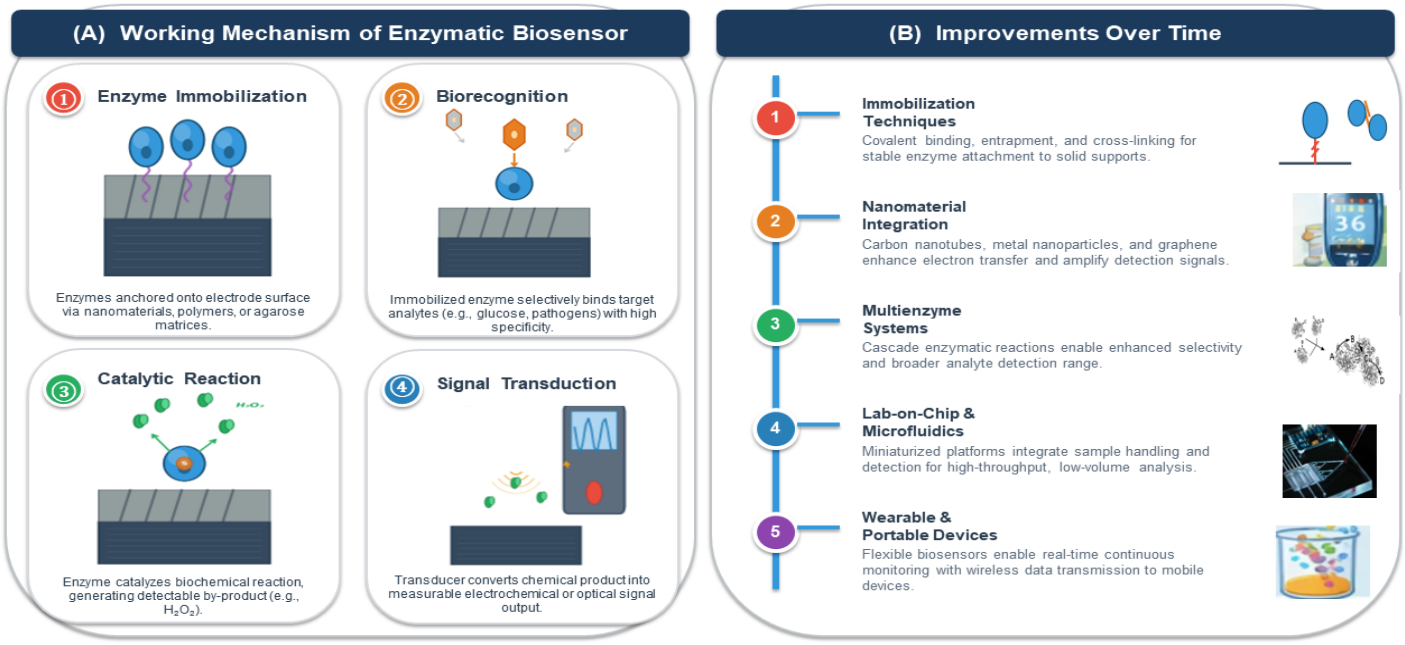


Figure 1: *Working mechanism and technological evolution of enzymatic biosensors. (a) The general working principles of an enzymatic biosensor: enzyme immobilization, analyte biorecognition, catalytic reaction, and signal transduction and (b) Development of new technologies in enzymatic biosensors, such as more sensitive and selective immobilization techniques, new nanomaterials, multienzyme cascade systems, lab-on-chip microfluidics, and wearable and portable biosensing devices increasing the sensitivity, selectivity, stability, and real-time monitoring capabilities of the biosensors.*

issues [10],[32]. Scientists are interested in the development of affordable, portable, and highly specific biosensors which can detect various diseases at an early stage and monitor environmental pollution [33],[34]. There is also great interest in creating sustainable biosensors which would help to preserve the environment while providing advanced medical and industrial achievements [35]. Recent advances in enzymatic biosensors include nanoaterial-assisted immobilization, microfluidic integration, multienzyme systems, and wearable sensing platforms as shown in Figure 1.

2. Carbohydrates-Degrading Enzymes

An important type of hydrolase is carbohydrate-degrading enzymes, which catalyse the breakdown of complex polysaccharides and oligosaccharides into simpler sugars, and are key players in natural metabolism and industry. They are broadly categorised as the Carbohydrate-Active Enzymes (CAZymes) system and have a few functionally different families, which are pectinases, cellulases, amylases or hemicellulases [36].

Despite the several recent reviews discussing enzyme-based biosensors, carbohydrate active enzymes (CAZymes), nanomaterial assisted sensing platforms and applications of food or environment biosensors, a detailed study focused on carbohydrate degrading enzymes (CAZymes) such as pectinases as biosensors is missing [37]. Currently, conventional oxidoreductases, like glucose oxidase, horseradish peroxidase and lactate oxidase, are the most frequently used in the literature for their analytical applications, while the use of pectinases, cellulases, amylases and hemicellulases in this field is comparatively less used [38]. This review combines uniquely the classification, catalytic mechanisms and production strategies of carbohydrate-degrading enzymes, their use in electrochemical, optical, colourimetric, and piezoelectric biosensors, immobilisation methods from traditional to nanomaterial-based, as well as new ideas such as nanozyme–enzyme hybrid systems, AI-assisted biosensing, wearable sensors, and sustainable sensor design. Special focus is given to pectinase-based biosensing for food quality monitoring, plant health assessment and the environment, which was not so well discussed in previous reviews [17].

2.1. Classification of Carbohydrate-Degrading Enzymes

Carbohydrate-Active Enzymes (CAZymes) include glycoside hydrolases (GHs), polysaccharide lyases (PLs), carbohydrate esterases (CEs), and auxiliary activities (AAs). In this system, individual GH families link to particular polysaccharide substrates. These pairings are the basis for selective biosensing tools [39].

Table 1
Comparison of Present Review with Recent Reviews on Enzymes-based Biosensors and Carbohydrate-active Enzymes

Review	Main focus	Pectinase/CAZyme biosensing coverage	AI/ Nanozyme coverage	Distributing Features Comparison	Ref.
Carbohydrate-active enzyme (CAZyme) discovery and engineering via (Ultra)high-throughput screening	Discovery, engineering, and screening technologies for CAZymes	No dedicated Biosensing discussion	Computational approaches discussed; no biosensor AI focus	Emphasized enzyme discovery and analytical sensing applications and transducer integration	[39]
A review on pectinase properties, application in juice clarification, and membranes as immobilization support	Pectinase properties, industrial application, and membrane immobilization	Pectinases only; no biosensing emphasis	No	Focuses on juice processing and immobilization supports, whereas the present review examines pectinases as biorecognition eleents in multiple biosensor platforms	[40]
Nanozymes towards Personalized Diagnostics: A Recent Progress in Biosensing	Nanozyme-enabled Biosensing using diagnostics	No	Extensive nanozyme coverage	Concentrates on artificial enzyme mimics, while the present review integrates natural enzymes with nanozyme-assisted sensing concepts	[41]
Advances in the understanding and exploitation of carbohydrate-active enzymes	Recent advances and applications of CAZymes in biotechnology	Minimal biosensing coverage	No	Review broad CAZyme applications in therapeutics, foods, and biofules, but not enzyme-based sensing mechanisms or immobilization strategies	[36]
Systematic review on lectin-based electrochemical biosensors for clinically relevant carbohydrates and glycoconjugates	Electrochemical Biosensing targeting carbohydrates and glycoconjugates	Uses lectins rather than carbohydrate-degrading enzymes	No	Focuses on carbohydrate recognition by lectins, whereas the present work emphasizes catalytic degradation by CAZymes as sensing elements	[42]
Present review	Pectinases and carbohydrate-degrading enzymes in Biosensing	Comprehensive coverage of pectinases, cellulases, aylases, hemicellulases, PME, PG, and PL	Comprehensive discussion of AI and nanozyme-assisted Biosensing	Integrates enzyme classification, catalytic mechanisms, production strategies, immobilization methods, applications	

Comparison highlighting the unique focus on pectinase-centered Biosensing, advanced immobilization strategies, nanozyme integration, artificial intelligence, and sustainable sensing technologies.

Pectinases (pectinolytic enzymes) break down pectin, a complex acidic polysaccharide of the plant cell wall composed of α-1,4-linked galacturonic acid units (usually methyl-esterified) with rhamnose and neutral side chains [43].

2.2. Structure and Catalytic Mechanism

Glycoside hydrolases contain active-site clefts or pockets that interact with polysaccharides and determine orientation of glycosidic bond cleavage sites [44].

The substrate specificity of glycoside hydrolases is determined by the configuration of active site clefts and their chemical properties. Therefore, enzymes that hydrolyse α-1,4 linkages in starch fail to hydrolyse β-1,4 bonds in cellulose. Polygalacturonase is an example of a glycoside hydrolase that specifically hydrolyses α-1,4-galacturonan chains, producing galacturonic acid and oligomers that can be analysed using electrochemical and optical biosensing methods [45]. Carbohydrate-degrading enzymes have been broadly studied for analytical applications due to their substrate specificity and ability to produce measurable products. Their major applications and characteristics are summarised in Table 2.

3. Pectinases: Types, Mechanism of Action and Production

3.1. Types of Pectinases

Pectinases are a class of enzymes involved in the degradation of pectic substances, complex polysaccharides rich in galacturonic acid and abundant in plant cell walls [43].

- **Pectin methylesterase (PME, E.C. 3.1.1.11):** PME causes demethylation of highly methylesterified pectin and yields methanol along with pectic acid. PME works around neutral pH (6-7) [43].
- **Polygalacturonase (PG, E.C. 3.2.1.15):** PG is involved in the hydrolysis of α-1, 4 glycosidic bonds present in the de-esterified pectin and forms galacturonic acid and its oligomers. Usually, fungal PGs found in Aspergillus niger and Trichoderma are active under pH 4-6 and temperature ranging from 30-50 °C, suitable for food processing and juice analysis purposes [51].
- **Pectin lyase (PL, E.C. 4.2.2.10):** Pectin lyase degrades highly methylesterified pectin by β-elimination reaction, forming unsaturated oligogalacturonates. This enzyme normally works best under slightly acidic and high temperature conditions (pH 6-8). It makes bacterial PLs appropriate for industrial applications and biosensors [52].
- **Pectate lyase (E.C. 4.2.2.2):** Pectate lyase acts on de-esterified pectin (pectate), but also acts through 8-elimination, producing unsaturated oligomers. It is typical in phytopathogenic and soil-dwelling bacteria like *Erwinia* and *Bacillus spp*., and tends to be higher in pH (7-9) than fungal PGs, which is suitable in wastewater or bioremediation-oriented biosensors [53].

3.2. Mode of Action

The structure of pectin involves mainly α-1,4 glycosidically bound D-galacturonic acids along with rhamnogalacturonans, methyl esters, and neutral sugars as side-chains [54]. PME cleaves methyl ester groups from the C6 carbon of galacturonic acid, resulting in the formation of methanol and an increase in the net charge density of the molecule. The latter can be used as an approach in biosensing by detection of methanol via alcohol oxidase activity or by observing changes in impedance and charges [55]. Pectin and pectate lyases act via β-elimination, providing the formation of unsaturated compounds absorbing light at 235 nm [56].

3.3. Sources and Production

The microorganisms represent the main source of pectinases used in industry due to their high productivity, amenability to genetic modification and characterisation of their catalytic properties [57]. Different fungal strains, such as *A. niger*, *A. oryzae*, *Trichoderma* and *Penicillium, secrete* acidic PGs and pectin lyases that are commonly used in food industries.

Large-scale production is carried out either by submerged fermentation (SmF) or solid-state fermentation (SSF). While SmF allows for good process parameter regulation and easy purification of the enzymes, SSF uses cheap agricultural residues such as citrus peels, wheat bran and sugarcane bagasse to increase enzyme yield [58].

4. Principles of Enzyme-Based Biosensing

4.1. Enzyme–Substrate Interaction in Detection

Table 2
Carbohydrate Degrading Enzymes and Their Use in Biosensing

Enzyme	Substrate	Reaction/ Product	Detection Method	Biosensing Application	Ref.
Pectinase	Pectin	Hydrolysis of pectin into galacturonic acid and oligomers	Electrochemical, colorimetric, pH-based sensors	Juice quality assessment, food analysis	[46],[47]
Polygalacturonase	Polygalacturonic acid	Cleavage of α-1,4-glycosidic bonds	pH-based and electrochemical methods	Detection of pectin, degradation in food samples	[48]
Pectin methylesterase	Methylated pectin	Removal of methyl groups	Electrochemical and colorimetric methods	Monitoring fruit maturation and pectin modification	[49]
Pectin lyase	Esterified pectin	Cleavage by β-elimination	Optical and electrochemical methods	Pectin content analysis in food processing	[50]

Overview of carbohydrate-degrading enzymes, their substrates, reaction products, detection methods, and biosensing applications.

Enzymes are used as biological recognition components in biosensors. They identify and catalyse reactions with specific target analytes. Pectinase breaks down pectin into galacturonic acid and related oligosaccharides for carbohydrate analysis [58].

4.2. Signal Generation Mechanisms

The main role of enzyme-based biosensor technology is to translate an enzyme reaction into a quantifiable analytic signal using one of several different transduction approaches such as electrochemical, optical or cholorimetric methods. Table 3 shows the comparative overview of major signal generation mechanisms.

4.3. Role of Reaction Products in Signal Output

The measurable products created by enzyme-catalysed reactions serve as the basis for how the enzyme-based biosensors produce output [66]. In the case of detecting pectin, pectinase catalyses the hydrolysis of pectin to yield galacturonic acid, resulting in a medium that is more acidic than before and monitoring the change is possible with many different sensors [67].

5. Role of Pectinase in Biosensing

5.1. Detection of Pectin and Plant-Based Substrates

Pectin is one of the larger components of plant primary cell walls and the middle lamella, providing adhesion and rigidity for plant cells. The softening of pectin during ripening, storage and infection is of agronomic significance and is largely controlled by the enzymatic degradation of pectin, so its monitoring has direct value in agriculture and food quality control [68].

Pectinases, namely pectin methylesterases (PME), polygalacturonases (PG) and pectin lyases (PL), which convert pectin to galacturonic acid and oligosaccharides (Figure 2), are the basis of several strategies of signal transduction: pH drop sensing (LOD ~0.15 U/mL pectinase) and chromogenic/absorbance-based detection at 540 nm [69]. The following two are examples of the trade-off in the field. Due to limitations in the buffering capacity and ionic strength of the sample matrix, pH-based detection is simple and label-free, but the quantitative accuracy in complex plant tissue extracts is limited. The colourimetric kits that utilise chromogens that are heated to react reach a similar sensitivity (0.15 U/mL) but require a reaction/heating step that increases reaction time and complexity that is difficult to implement in the field [70]. This enzyme-reactive nanofiber packaging technology is extended to provide a real-time, in-line or in-package spoilage indicator, not a discrete assay; an important benefit, but at the cost of less quantitative information and less sensitivity to false-positive and false-negative results under fluctuating humidity/temperature storage conditions in the product are less well characterised [47].

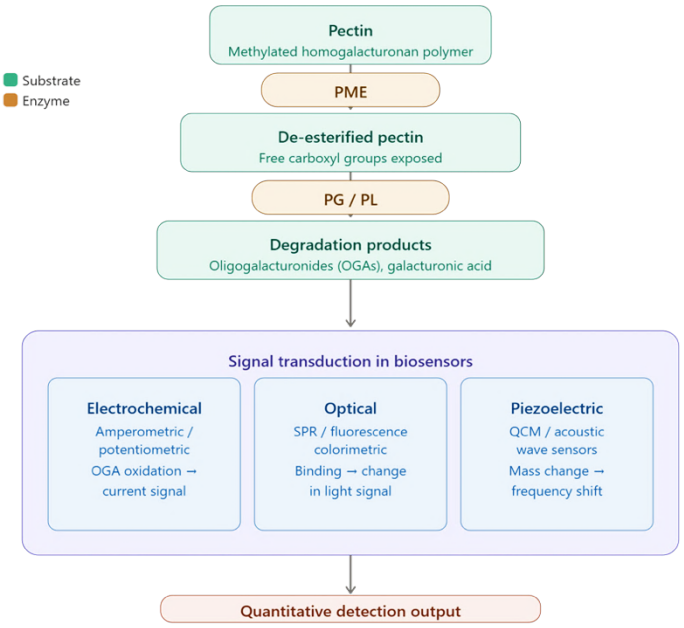


Figure 2: *Mechanism of pectin breakdown and biosensor signal transduction: Enzymatic degradation of pectin by PME and PG/PL results in oligogalacturonides that carry out signal transduction across electrochemical, piezoelectric, and optical biosensor platforms.*

5.2. Pectinase-Specific Biosensing Platforms

Apart from the mentioned pH drop and heated chromogenic systems, several biosensor designs have been developed based specifically on the recognition chemistry of pectinases, varying in the way the event of pectin hydrolysis is detected [7].

Assays utilising polygalacturonan substrates conjugated with dyes such as Remazol Brilliant Blue (RBB) offer a direct measurement of cleaved chromophore fragments produced without any heating, thus reducing the time of the analysis compared to the DNS assay requiring heating, yet maintaining the same sensitivity range. Analogous fluorogenic assays use substrates labelled with fluorescein or coumarin, providing increased sensitivity for low enzyme concentrations at the expense of using fluorescent labels [71]. Mass- and refractive index-based biosensors, Quartz Crystal Microbalance (QCM) biosensors coated with a thin layer of pectin, provide detection of enzymatic activity through real-time mass change, while Surface Plasmon Resonance (SPR) biosensors detect enzymatic activity through change of refractive index due to

Table 3
Signal Generation Mechanism Mostly Used in Enzyme-Based Biosensing Systems

Mechanism	Signal Type	Enzyme-Based Detection	Advantage	Reference
Electrochemical	Current, voltage, impedance, conductivity	Detection of electrical signals	High sensitivity, rapid response, easy miniaturization, suitable for real-time monitoring	[7],[59]
Optical	Absorbance, fluorescence, luminescence, refractive index	Detection of change in light intensity or fluorescence	Non-destructive analysis, high specificity, multiplex capability	[60],[61]
Colorimetric	Color intensity change	Detection of color change visually or spectrophotometrically	Simple operation, low cost, no sophisticated instrumentation required	[62]
Piezoelectric	Frequency or mass variation	Detection of change in crystal mass and resonance frequency	Label-free detection and high sensitivity	[63],[64]
Thermal (Calorimetric)	Change in temperature	Monitoring of heat change	Direct measurement without labels or dyes	[65]

Signal generation mechanisms used in enzyme-based biosensors and their applications.

hydrolysis of pectin. Both biosensors are label-free and provide continuous kinetic curves, which can be useful for studies of enzyme kinetics, yet QCM/SPR instrumentation is expensive and bulky [45].

Immunosensors and aptasensors are directed at the pectinase enzyme itself. Rather than measuring the hydrolysis products, immunosensors or aptasensors using antibody- or aptamer-functionalized electrode surfaces and SPR chips could measure the pectinase enzyme itself, which may be more suitable when the detection of a specific form of the enzyme is important [72], e.g., the polygalacturonase produced by phytopathogenic fungi like Botrytis cinerea or Verticillium spp. as an early sign of infection before the development of any visible symptoms. While the ability to detect individual isoforms is a real advantage over bulk activity assays, the cost and variability of antibodies/ aptamers production make it hard to use routinely [73].

Whole-cell and microbial biosensors. Genetically modified bacteria or yeast cells, which contain pectin-inducible promoter linked to genes encoding fluorescent protein (GFP) or luciferase reporter, serve as self-amplifying and cheap method for detection of pectinases in the environment or agriculture. As the output relies on the processes of transcription and translation, the reaction rate is lower compared to cell-free methods; moreover, viability issues reduce the portability of the technique [74]. Nevertheless, the

Table 4
Different Methods of Biosensing Systems

Method	immobilization	Sensitivity/LOD	Linear Range	Stability	Response time	Application	Ref
MBTH colorimetric assay for pectinase activity	Free pectinase using an optimized MBTH-based chromogenic reagent for reducing sugar detection under high alkaline and low temperature condition	Low LOD, High sensitivity (R^2= 0.9945)	2.5-15.8 mU/mL	Resolve background-interference and pectin precipitation problem of earlier DNS/MBTH protocol	Zero-order hydrolysis kinetics within 60 min; endpoint measurement	Enables routine; accurate quantification of pectin/pectinase depolymerase activity for industrial and research QC	[71]
Quartz crystal microbalance with dissipation (QCM-D) continuous assay	Insoluble polygalacturon-calcium immobilized on quartz sensor surface	Not a calibrated concentration LOD-continous kinetic-rate assay	Not applicable	Facilitate comparative analysis of enzyme preparation without requiring multiple sample	Continuous, dissipation trace and real time mass loss	Bench-top research tool for comparative kinetic analysis of endo-pectinase (e.g; GH28-family) mediated degradation activity on solid phase pectin substrate	[45]
Smartphone-read (paper based lateral flow strip	Smartphone based detection of Enzyme-mediated pectin viscosity changes measured by diffusion distance on pH indicator paper strip	0.025 U/mL	0.025-0.80 U/mL	-	Single endpoint diffusion readout	Field-deployable rapid screening of PG activity, Low cost	[56]
Pectinase immobilized on magnetic nanoparticles using PEG-trichlorotriazine chemistry	Pectinase immobilized covalently on PEG-grafted magnetic nanoparticles through trichlorotriazin coupling	-	Not applicable	94% retained after 125 days; 55% of activity retained after 10 cycles, store at 25°C	-	Immobilized enzyme mediated clarification of pineapple juice, reducing turbidity to 59% following 120 min of treatment	[69]
Fluorescent SWCNTs based biosensor for real time pectinase activity monitoring	Pectin-coated (6,5)-SWCNTs; enzyme pectin degradation promote fluorescence quenching and SWCNT aggregation and	-	Not reported	Not reported	Continous fluorescent readout, real time	NIR based real time monitoring of pectinase activity in process/biological specimen	[77]

whole-cell systems are convenient if in situ continuous monitoring is required. While the sensor signal relies on transcription/translation in cells, and not enzymatic activity, this results in a delay in response and portability issues due to the need to maintain the viability and culture status of cells. The method is promising when continuous in-situ detection becomes a priority, as opposed to fast single-point determination of an analyte concentration [75].

Molecularly imprinted polymers (MIPs) as synthetic receptors. MIPs obtained by imprinting galacturonic acid or pectinase itself are under investigation as cheaper and more robust chemical and thermal alternatives to antibodies for use in immobilisation formats. Low reproducibility of the imprinted cavities and relatively slow rebinding rate of MIP-based sensors make such pectinase sensors less sensitive than those employing antibodies and aptamers, yet the cost and stability of MIPs make the platform worth watching [76],[77],[78],[79],[80].

Overall, along with pH, chromogenic, electrochemical, nanoparticles-immobilised, and paper-based lateral flow platforms already described in this paper, there are at least eight different pectinase-specific platform classes known now, as mentioned in Table 4. None of the existing classes prevails: all of them occupy their own positions in the sensitivity, speed, cost and portability spectrum, and therefore the selection of the right platform should be based on its application [56].

5.3. Analytical Use of the Pectin Degradation Products

The principal product of the backbone of pectin being cleaved is galacturonic acid (GalA) and most pectinase biosensing chemistries are based on the detection of this product, but there are significant variations in sensitivity, speed, and infrastructure requirements. Well-established and economical, they are bulk end-point measurements that sacrifice spatial or kinetic resolution, as well as being potentiometric and optical detection of the associated pH drop (which is detected colourimetrically using DNS-reagent assays at 540 nm) [69]. Enzymatic sensors that monitor the current/impedance changes of the enzymes on the electrodes provide real-time kinetic readout, which is beneficial for the study of enzyme kinetics, but tend to be more complicated to fabricate and calibrate electrodes than colourimetric sensors. At the other end of the spectrum, however, are the paper-based lateral-flow strips that read PG activity by diffusion distance [56], which are low-cost and field-deployable, but less precise than electrochemical or nanomolar-sensitivity catalytic amplification approaches [98]. The net picture is not that of a single best way, but one of a sensitivity/throughput-vs-simplicity trade-off: nanomolar-sensitivity amplification assays work well for detailed kinetic or diagnostic work; lateral-flow strips work well in the field for rapid screening; and no single current platform combines both [81].

5.4. Recent Technological Advances

Nanomaterials other than graphene or gold nanoparticles, MXenes (Ti_3C_2Tx and other two-dimensional transition-metal carbide/nitride materials), have recently emerged as candidates in the wider domain of electrochemical biosensors that would combine conductivity with the hydrophilicity and surface functionalisability appropriate for enzymes [82]. Their potential use as a component in pectinase or pectin sensing has not yet been reported in the reviewed literature, but it constitutes a readily available possibility rather than an advance made by this subfield, as indicated here: production of wearable and flexible electrodes via printing technology [83]. Flexible substrate and screen-printing technologies, mainly developed for wearable electrochemical biosensors in healthcare applications, would enable inexpensive, disposable, in-line measurement of pectinase activity in the packaging line or in juices and wines. Similarly to MXenes, this represents an advance in biosensors that can be applied in pectinase detection but has not yet been achieved by pectinase biosensors themselves [84].

Signal processing using machine learning. In enzyme detection and food quality monitoring in general, machine learning approaches are being used more and more often to account for matrix effects and for the combination of signals from various sensor outputs. In the case of pectinase sensing, this can be translated to integrating pH, colourimetric, and impedance channels into a single ripeness/spoilage metric [85]. Chromogenic or fluorogenic pectinase detection assays coupled to smartphone camera-based colour analysis software get rid of the requirement for a benchtop spectrophotometer, bringing lab-validated assay chemistries closer to practical field applications. One of the more developed technologies among those described in this section, smartphone-readout colourimetric devices have already been proven for use with other food-quality chemistries and need only an assay adaptation, not device development, for pectinase detection [62].

5.5. Future in New Biosensing Systems

The two most prominent levers for advancing pectinase biosensors beyond some of the above-detailed limitations are nanomaterial integration (such as graphene, AuNPs, conducting polymers) and microfluidics. A major advantage of nanomaterials is that they have a significantly higher surface area (100-1000 times higher) and electron-transfer rate (10-50 times) [86] than in the other systems described above, in addition to immobilization stability (80-90% activity retained after 10-20 cycles) [87], which directly overcomes the reusability and the sensitivity restrictions of the electrochemical and immobilized-enzyme systems. Microfluidic/lab-on-chip formats solve the throughput and matrix-interference issues mentioned above by using small volumes (<100 nL) and can provide high-throughput (100-sample) screening, fast impedance-based readout (<5 min) and improved signal quality (SNR>20 dB), but require less sample (10-100×) than the microplate format [88]. Real-world gains are achievable, but most of them have been demonstrated individually and/or under controlled laboratory conditions, and the challenge now is to make these novel functions available as a single validated platform for real, variable food or environmental matrices, which are not ideal buffers. While applications like anthocyanin-based indicators of food spoilage in smart packaging, pathogen detection in precision agriculture or diagnostic applications are promising, they are still largely in concept and reproducibility, cost-per-test and shelf stability under real storage/transport conditions are the greatest barriers to translation from bench to field [89]. There are four such opportunities that come out of the platform review listed above and should be explicitly stated rather than left implied. First, multiplexed assays: using probes selective for PME, PG, and PL enzymes together on a single chip or strip will result in a compound ripeness or spoilage indicator, thus tackling the sensitivity-vs-simplicity dilemma [88]. Second, logistics-integrated sensing: integrating in-package or in-line pectinase detection with wireless sensing (RFID, NFC, or IoT) will enable continuous ripeness/spoilage monitoring along the entire cold chain from storage through distribution to retail, as opposed to the one-shot readings that predominate among the platforms reviewed [90]. Third, sustainable biodegradable sensor materials: paper-, cellulose-, or biopolymer-based sensing platforms will make pectinase sensors conform to the emerging trend of biodegradable smart packaging, without adding to the electronic waste generated by what is often compostable packaging [70].

Fourth, validation and standardisation: practically all the developments covered in this chapter, from nanomaterials immobilisation to microfluidic designs and thermostable enzyme variants, have been tested individually in controlled lab conditions [80]. What now stands between us and the real-world application of these devices is not the discovery of new chemistries, but rather the validation of such a system as a whole against real food and environmental matrices and setting the reproducible cost per test figures; not to mention inter-laboratory experience needed before any standards acceptance at the industry level. Prioritising these practical considerations will contribute more significantly to advancing next-generation pectinase biosensors than continued development of standalone proof of concept studies.

6. Applications of Enzyme-Based Biosensors

The capability to detect biochemical substances in real time, rapidly, and sensitively has seen biosensors widely used in various fields. These devices combine both biological recognition components and transducers to detect physical, chemical and biological processes. Their versatility allows their use in food safety, environmental surveillance, in controlling industrial processes, and in biomedical diagnostics and makes them an essential part of a modern analytical system [10] as shown in Figure 3.

6.1. Food Quality and Safety Monitoring

One of the most important fields in biosensor applications is food quality and safety monitoring. Conventional methods of analysis that are being used in food industries tend to be time-consuming and involve the use of skilled personnel; biosensors are fast, cost-effective, and highly selective in detecting contaminants and quality indicators [91]. Biosensors have been extensively applied in the processing of fruit juice, to monitor glucose level and sugar composition variation in storage and preparation of fruit juice. The glucose biosensors are of great significance since the food products might alter in their composition during storage, thus influencing the quality and nutritional value [92]. The application of glucose oxidase immobilised on electrodes that have been modified with gold nanoparticles has been reported to enhance the level of sensitivity in the detection of glucose in food products like juices and beverages [93].

The microbial contamination and spoilage detection in food systems are also critical in the use of biosensors. As an illustration, Escherichia coli can be detected in vegetables and this is an indicator of fecal contamination. This is done by measuring changes in pH or impedance changes brought about by the metabolites or ammonia using potentiometric or impedance biosensors [94]. These systems can quickly identify contamination and are useful in ensuring food safety standards. Biosensors are also used in the dairy industry to identify pesticide and herbicide residues and other contaminants. Recently, polymer-based and nanomaterial-based biosensors have been developed to be used on-site to detect heavy metals, antibiotics, allergens, and pesticide residues in milk and other food samples [95]. Biosensors based on automated flow that combine enzyme systems and automation have also been created to analyze the quantity of the organophosphate

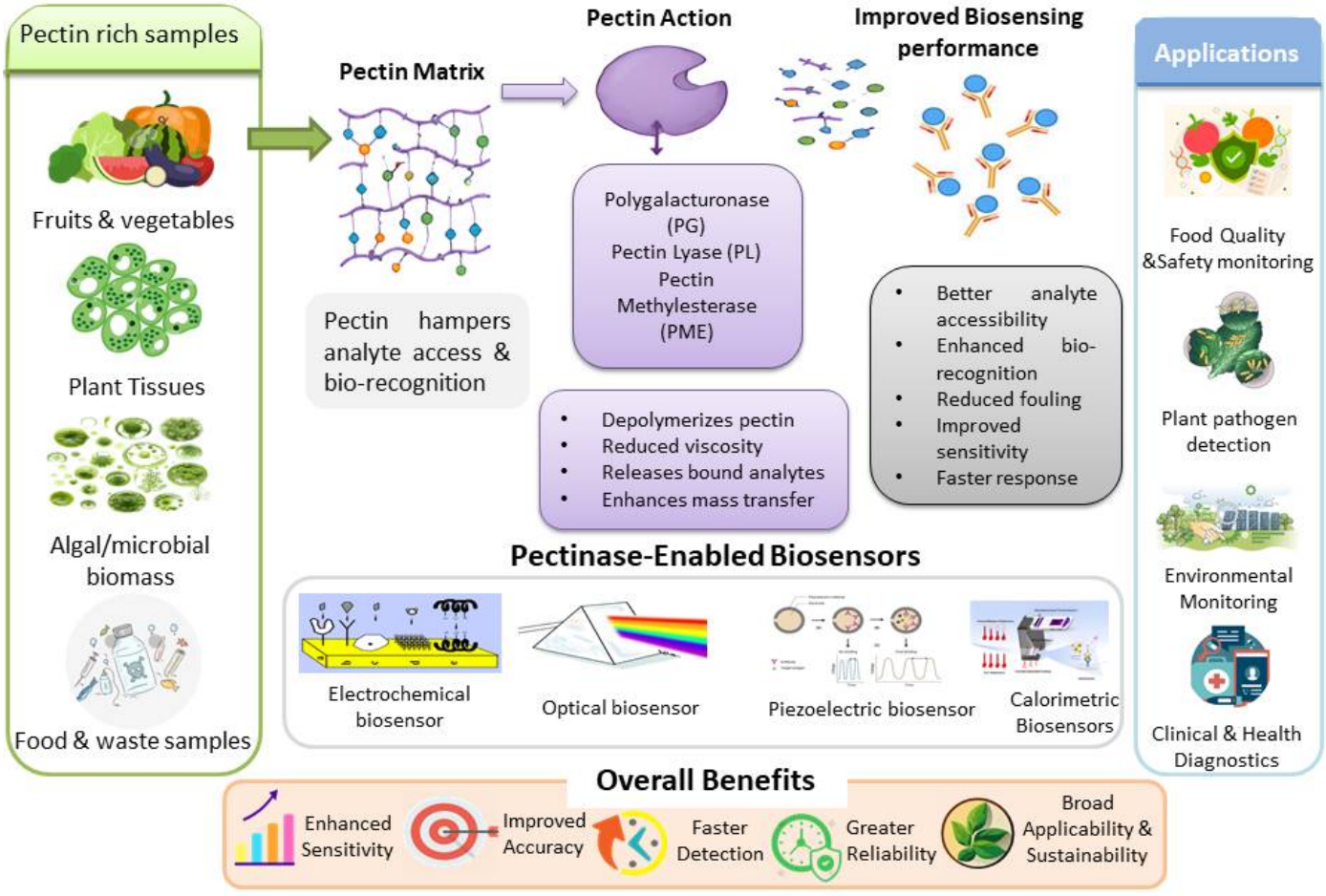


Figure 3: *Applications of pectinase in biosensors. Enzymatic degradation of pectin by PG, PL, and PME enhances analyte accessibility and signal generation improving the performance of biosensor across environmental, clinical and food applications..*

and carbamate pesticides in the milk sample, guaranteeing food safety and adherence to regulations [96]. Recent developments highlight the use of immunosensors and CRISPR- or nanozyme-based biosensors for pathogen detection (e.g., E. coli, Salmonella, Listeria) with improved sensitivity, specificity, and field-ready operation. All in all, biosensors play a vital role in food quality assurance, spoilage prevention, and consumer safety due to continuous and on-site monitoring and rapid detection systems [97].

6.2. Environmental Monitoring

Another important field of biosensor use is in environmental monitoring. These instruments make it possible to detect pollutants, poisonous substances, and biological pollutants in water, soil, and air in a short time. Their selectivity and sensitivity enable them to be detected at very low concentrations [35]. A significant application is in biomass degradation and waste analysis, where biosensors are employed to measure biochemical oxygen demand (BOD), variations in organic load, and metabolic activity. Whole-cell biosensors have also been invented to sense heavy metal ions via metallothionein or metal-responsive promoters of microorganisms [98]. These biosensors are specific to toxic metals and thus can be used as tools in monitoring pollution in the environment as well as ecological risks. Pesticide residues are also detected using biosensors and these are major hazards to the environment. Biosensors based on enzymes have been developed to identify the presence of organophosphate and carbamate pesticides in water samples by using the enzyme acetylcholinesterase (AChE) and butyrylcholinesterase [99]. These biosensors are fast in response and sensitive, and thus they can be used in real-time monitoring of the environment. Moreover, biosensors based on nanomaterials, as well as bacterial bioassays, have been utilised to detect arsenic, cyanide, and other toxic metals in natural water sources [35]. These systems offer dependable identification of harmful materials and help in protecting the environment. In general, biosensors are more environmentally friendly because they allow quick and sensitive detection of pollutants and efficient waste- and water-management mechanisms.

6.3. Industrial Process Monitoring

Biosensors are also important in industrial biotechnology to monitor the production processes and improve the efficiency of the operations. Fermentation and bioconversion processes are among these and they are major areas of application. The process of fermentation is complicated and entails various biochemical reactions, during which strict regulation of the metabolites, including glucose, lactate, ethanol and amino acids, is critical [100]. To monitor these compounds in real time, biosensors have become common to enable better product yield and better control over the processes. The glucose biosensors used in modern fermentation industries are more accurate in controlling the saccharification and fermentation processes as opposed to the traditional titration methods.

Fermentation systems have been enhanced greatly with the application of biosensors to help with better productivity. As an illustration, biochemical changes in an ion-exchange process of fermentation systems have been monitored using glutamate biosensors [101]. Critical metabolites are detected in real time, and process conditions can thus be optimised more quickly and the product quality is maintained. Biosensors also contribute to the conversion processes of bioconversion processes where biological materials are changed into valuable products such as enzymes, organic acids and biofuels [98]. The ability to monitor metabolic activity using biosensors online can help maintain better control of reaction conditions and improve efficiency. Recent developments have incorporated microfluidic and lab-on-chip biosensors in bioprocess control systems, which have enabled high-throughput, automated and miniaturised monitoring of bioreactors in industries. All in all, biosensors are useful tools in current biotechnological industries as they offer automated, fast and reliable monitoring of the industrial process [88].

6.4. Emerging Biomedical Applications

One of the most rapidly developing areas of biosensor technology is biomedical applications. These applications aim at diagnosing diseases, monitoring health and early detection of biological markers of several medical conditions. The glucose biosensor is one of the most popular biosensors that are currently utilised in healthcare and is widely used to monitor the levels of blood glucose in patients with diabetes mellitus [102]. These devices can be monitored around the clock or nearly 24 hours and they give precise readings, which are required in the management of a disease. A high percentage of the biosensor market worldwide is taken by blood glucose monitoring systems because of their extensive clinical applications.

Detecting infectious diseases and pathogens is also done by using biosensors. Immunosensors, DNA biosensors, and CRISPR-based biosensors are rapidly developing biosensor technologies which can be used to identify microbial infections, including urinary tract infections, bacteria that cause sepsis, and viral infections (e.g., SARS-CoV-2, influenza) [103]. These devices minimise the time of diagnosis, aid in point-of-care testing, and enhance treatment outcomes. The other biomedical application that is emerging is the detection of cytokines and biomarkers related to inflammation, such as interleukin-6 (IL-6), interleukin-10 (IL-10), and tumour necrosis factor-alpha (TNF-alpha), which are involved in inflammatory reactions as well as cardiovascular or autoimmune disorders [104]. Advanced materials like hafnium oxide, graphene or antibody-functionalized electrodes have been developed as biosensors to enable detection of disease-related biomarkers in their early stages to allow timely medical intervention [105]. The latest developments in antibody- and aptamer-based biosensors have broadened the scope of detection of cancer biomarkers, cardiac markers and neurochemical species in blood, serum and even in vivo. Moreover, the biosensor based on carbohydrate-protein interaction has been investigated to detect pathogens [106]. Lectin carbs the biosensors read lectin-carbohydrate recognition to detect microbial targets like E. coli and other bacteria that have particular surface glycans. As an example, mannose or other sugar-functionalized surfaces have the capacity to bind bacterial pili, resulting in detectable impedance or piezoelectric responses, enabling label-free and specific detection of pathogens. In general, the new biomedical biosensor technologies have great potential in the field of enhancing diagnostic accuracy, personalised medicine and point of care medicine, and in improving healthcare delivery system [5].

7. Challenges and Limitations

Despite the widespread use of enzymes in biosensors and industrial biotechnological processes, some issues affect the efficiency and applicability of enzymes and become especially important regarding the commercialisation of pectinase biosensors [80].

- **Enzyme stability:** One of the major limitations of using enzymes is related to their instability and loss of activity during storage and operation. Enzymes are highly labile biological molecules whose catalytic properties depend upon several external factors, including temperature, pH and ionic

strength [86]. Nevertheless, inappropriate use or lack of control of the operating conditions may lead to denaturation or conformational changes in the enzyme, which results in the decrease of catalytic properties and reduction of the lifetime of the enzyme [107]. In the case of pectinases, this problem is particularly significant because of their highly selective catalytic properties that work in rather narrow pH and temperature windows. Exposure to various matrices containing acids, sugars and different temperatures that accompany analysis of fruit juices and other food samples may result in the rapid decay of pectinases' activity and reduced shelf life of the sensor [69].

- **Sensitivity:** The lack of sensitivity, which can be observed in some systems, is another limitation that affects detection of very low concentrations of analytes. In some cases, when it is important to detect very low concentrations of something in diagnostics, environmental monitoring, or analysis of food quality, insufficiency of the sensitivity of enzymatic systems could become a problem [108].
- **Structural heterogeneity of the substrate:** One more often underestimated limitation of pectinase-based systems is that of the structural heterogeneity of the substrate – pectin. The structure of the pectin differs from sample to sample and depends on the plant, its stage of ripeness, etc. Moreover, there exist several types of enzymes that belong to pectinases (polygalacturonases, pectin lyases, pectin methylesterases, etc.). Therefore, the biosensor that was calibrated on some particular pectin source will not necessarily work well with others, which makes assay development quite complicated [109].
- **Matrix interference:** Moreover, sample matrix interference might impact the efficiency of the enzyme and the analysis itself. There are many components such as inhibitors, organic matter, salts, and proteins contained in biological fluids, food, and environmental samples that may interact with the enzyme-substrate reaction and give misleading results [110]. Interference in the matrix will result in a lack of specificity of the response and false positives and negatives. This is especially important for pectinase biosensors since food and juices contain sugar, have variable pH, and have other polysaccharides that can interfere with the reactions [69].
- **Issues in high-volume manufacture:** Besides the issues with performance in the lab, scaling up of the pectinase biosensor manufacture process is also associated with its specific problems. Obtaining and purifying enzymes at a high volume is a challenge in itself due to batch to batch variations of activity and purity, immobilization techniques that worked well on hand-made electrodes sometimes don't scale up easily, and especially nanomaterial-based enzyme immobilization [111]. In addition, the cold-chain requirement and short shelf-life further increase complications associated with distribution and cost, which can act as practical limitations towards making a pectinase biosensor transition from prototype into a commercially available device [112].
- **Standardisation and reproducibility:** Additionally, standardisation becomes another issue when developing and commercialising technologies based on enzymes. Differences may occur in terms of enzyme activity within different studies and laboratories due to differences in the enzyme source, enzyme purification, enzyme immobilisation, conditions of assay and used analytical techniques [113]. There are no standard protocols; therefore, it becomes difficult to reproduce results and compare the outcomes of experiments. In the case of pectinase biosensors, the problem of non-standardised reference substrates and assays increases the problem of results comparison and the creation of a standard protocol necessary for validation and commercialisation [114]. When put together, enzyme instability, substrate variability, matrix interference, scale-up manufacture, and lack of standardised methodology for analyses make up an intricate set of obstacles that prevent the transfer of pectinase biosensors from laboratory prototypes to commercial applications. Therefore, stabilisation of enzyme, enhanced sensitivity, consideration of variability of pectin substrates, elimination of matrix interference, creation of reproducible manufacturing technology, and development of standardised methodology become important tasks for the future progress of the reliability of enzyme-based systems [115].

8. Future Perspectives

It is expected that future development of enzyme-based biosensing techniques will concern the improvement of performance, wider implementation of the technology, and sustainability. An approach to the engineering of enzymes by protein engineering, directed evolution and genetic manipulations is a relatively new method for the optimisation of enzymatic catalysis, specificity of reactions, thermal stability, and environmental stress resistance of the enzymes. As for pectinases, directed evolution or rational engineering aimed at increasing pH and thermal stability or reducing the influence of substrate heterogeneity may be applied for overcoming two of the main challenges of pectinase biosensors. Enzyme degradation and reduced activity limitation issues can be overcome by these means.

- **AI-assisted Biosensing:** More advanced integration of artificial intelligence and machine learning techniques with enzyme-based sensors is expected. In the case of pectinase biosensors, this approach may be useful for the differentiation of a complex response generated by the heterogeneity of pectin structure and interference from sugars, salts, and other polysaccharides in the juice or food matrix, thus providing adaptive calibration. Machine learning techniques can be employed for compensating for baseline drift due to reduced enzymatic activity of the sensor throughout its operational lifetime, thus prolonging the usable life of sensors without the need for recalibration after each production batch, as well as detecting any unusual measurements that can be attributed to the presence of interferents rather than actual changes in concentration of the analyte.
- **Hybrid pectinase-nanozyme biosensors:** Nanozymes are nanomaterials possessing enzyme-mimicking catalytic properties and have been investigated as partners and even potential substitutes for natural enzymes in designing biosensors. The use of a hybrid of natural pectinase and a nanozyme may provide an opportunity for decoupling the performance of the biosensor from the instability of the enzyme by maintaining the catalytic reaction and signal transduction despite the gradual decrease in activity of the natural pectinase, thus making it possible to achieve greater stability and longevity beyond the possibilities of just the immobilisation of the enzyme. This type of approach is quite consistent with the previously mentioned approaches of using nanomaterials in biosensors due to the identical nature of materials.
- **Flexible and wearable biosensors:** Although most of the current biosensor applications involving pectinase focus on food quality or environmental monitoring, not wearable healthcare, the flexible substrate technologies used for wearable sensors are gaining importance for pectinase tests

carried out using decentralized, mobile, field-based equipment such as flexible sensors in strips or patches that are used to assess the ripeness of fruits or quality of their juice in harvesting, processing, or transportation stages, not only in stationary laboratories. The use of flexible electrode material and printing techniques to immobilise pectinase would help here.

- **Microfluidics integration:** Combining pectinase biosensors with microfluidic devices provides a direct solution to overcome many of the barriers to commercialisation. The integration of microfluidics in the process of biosensing allows to standardize the sample volume, dilution, and pretreatment of heterogeneous samples containing pectin. In addition, microfluidic integration combined with small-scale reagents and enzyme storage helps to achieve the kind of small-volume, automated, and reproducible preparation needed for scaling up from manually assembled research electrodes.
- **Multiplex sensing platforms:** Since pectin breakdown is only one parameter among several that indicate the quality of food/juice (along with other parameters such as sugar content, acidity, or spoilage markers, for instance), the development of multiplexed sensing platforms which integrate detection based on pectinase with other enzymatic or non-enzymatic sensing channels into a single chip will allow obtaining a comprehensive profile of food quality with a single sampling/measurements process. Besides being able to compensate for the lack of sensitivity and selectivity of any one enzymatic channel, multiplexing will allow validating results through multiple parallel measurements. Moreover, increasing demand for fast, accurate and non-invasive disease detection methods will definitely contribute to the increased application of enzyme-based biosensors in medical diagnostics in the future. Biosensors can be used for early disease detection of metabolic disorders, tumour markers, infectious diseases and personalised medicine approaches. Health monitoring in real time is sure to be enhanced due to the use of modern technologies, including artificial intelligence and wearable sensors. In addition, the creation of environmentally sustainable biosensors has become an important field of research with an emphasis on environmentally friendly materials, biodegradable materials, environmentally sustainable synthesis, and energy-saving production. This is a type of development that corresponds to the global aims of sustainability and can assist in reducing environmental impact without compromising the analytical capabilities of these sensors.

All of the above-mentioned trends in combination constitute the way to implement the concept of pectinase biosensor into practice through creating a robust, deployable, and economically efficient sensor. Biosensors based on enzymes are expected to find widespread applications and make a breakthrough due to the continuous improvements in the areas of enzyme engineering, hybrid systems design, and clinical applications.

9. Conclusion

Carbohydrate-degrading enzyme-based biosensors represent an emerging frontier in intelligent sensing technologies, offering exceptional molecular recognition, catalytic specificity, and versatile analytical capabilities. Among these systems, pectinase-based biosensors provide unique opportunities for monitoring food quality, plant health, environmental changes, and industrial processes through selective detection of pectin-related biochemical transformations. Recent advances in nanomaterial-assisted immobilisation, microfluidic integration, flexible sensing platforms, and sustainable biomaterials have significantly improved sensor performance, stability, and practical applicability. However, challenges associated with enzyme stability, substrate complexity, matrix interference, reproducibility, and large-scale manufacturing continue to limit real-world deployment. Future progress will depend on the synergistic integration of enzyme engineering, advanced functional materials, and intelligent data-driven sensing architectures. By addressing these limitations, carbohydrate-active enzyme-based biosensors are expected to evolve into robust, portable, and sustainable analytical platforms, contributing significantly to next-generation healthcare, food safety, environmental monitoring, and industrial biotechnology.

Declaration

AI Disclosure: N/A

Author Contribution Statement: R. U. wrote this paper.

Availability of Data and Materials: Data will be made available by the corresponding author on reasonable request.

Competing Interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Issues: There are no ethical issues.

References

1. Gao, W., et al., Recent advances in biosensors: Structure, principles, classification, and application in bio-manufacturing. Methods, 2025. 242: p. 123-142.
2. Sharma, S., R. Butola, and J. Kumar, Transforming Industry: The Role of Biosensors in Enhancing Efficiency, Safety, and Sustainability. ECS Journal of Solid State Science and Technology, 2025. 14(5): p. 057001.
3. Guo, J., et al., Effect of deep eutectic solvents on the activity and stability of cellulases and pectinases. ACS omega, 2023. 8(48): p. 45678-45686.
4. Khor, S.M., et al., Challenges and strategies in developing an enzymatic wearable sweat glucose biosensor as a practical point-of-care monitoring tool for type II diabetes. Nanomaterials, 2022. 12(2): p. 221.
5. Elgiddawy, N. and H.M.E.-S. Azzazy, Carbohydrate-based biosensors for enhanced pathogen detection. Analytical and Bioanalytical Chemistry, 2025: p. 1-22.
6. Eivazzadeh-Keihan, R., et al., Recent advances on biomedical applications of pectin-containing biomaterials. International journal of biological macromolecules, 2022. 217: p. 1-18.
7. Wijayanti, S.D., L. Tsvik, and D. Haltrich, Recent advances in electrochemical enzyme-based biosensors for food and beverage analysis. Foods, 2023. 12(18): p. 3355.
8. Wang, X., J. Zhou, and H. Wang, Bioreceptors as the key components for electrochemical biosensing in medicine. Cell Reports Physical Science, 2024. 5(2).
9. Khaleque, M.A., et al., Bioreceptor modified electrochemical biosensors for the detection of life threating pathogenic bacteria: a review. RSC advances, 2024. 14(39): p. 28487-28515.
10. Assudani, P.J., et al., Biosensing technologies for foodborne pathogen detection and healthcare: principles, emerging materials, and intelligent platforms. Microchimica Acta, 2026. 193(4): p. 231.
11. Singh, R., et al., Advancements in glucose biosensors: Innovations for wearable and real-time monitoring. Talanta, 2025: p. 129045.
12. Chen, K., et al., Exploring nucleic acid nanozymes: a new frontier in biosensor development. Biosensors, 2025. 15(3): p. 142.
13. Zhao, J., et al., The advancement of biosensor design and construction utilizing biomolecular motors. Synthetic and Systems Biotechnology, 2025. 10(2): p. 543-554.
14. Hussain, A., et al., Recent Advances in Integrating Graphene into Polymeric Nanocomposite Hydrogels for Biomedical Applications. Macromolecular Bioscience, 2026. 26(2): p. e00553.

15. Malode, S.J., et al., Bio-based nanomaterials for smart and sustainable nano-biosensing and therapeutics. Industrial Crops and Products, 2025. 234: p. 121603.
16. Khumngern, S. and I. Jeerapan, Synergistic convergence of materials and enzymes for biosensing and self-sustaining energy devices towards on-body health monitoring. Communications Materials, 2024. 5(1): p. 135.
17. Melo, R.L.F., et al., A comprehensive review on enzyme-based biosensors: advanced analysis and emerging applications in nanomaterial-enzyme linkage. International Journal of Biological Macromolecules, 2024. 264: p. 130817.
18. Kausaite-Minkstimiene, A., et al., An amperometric enzyme–nanozyme biosensor for glucose detection. Biosensors, 2025. 15(8): p. 545.
19. Kumar, A. and P. Maiti, based sustainable biosensors. Materials Advances, 2024. 5(9): p. 3563-3586.
20. Nazreen, A., et al. Biopolymers-based Electrochemical Sensors: An Overview of Synthesis and Applications. in Acta Biol. Forum. 2024.
21. Guoqiang, G., et al., Recent advances in glucose monitoring utilizing oxidase electrochemical biosensors integrating carbon-based nanomaterials and smart enzyme design. Frontiers in Chemistry, 2025. 13: p. 1591302.
22. Williams, A., et al., Biosensors for public health and environmental monitoring: the case for sustainable biosensing. ACS sustainable chemistry & engineering, 2024. 12(28): p. 10296-10312.
23. Sun, G., et al., Immobilization of enzyme electrochemical biosensors and their application to food bioprocess monitoring. Biosensors, 2023. 13(9): p. 886.
24. Han, Y., J. Wei, and W. Feng, Hybrid of glucose oxidase and enzyme-like Cu&Ce: Efficient glucose scavenging and generation of hydroxyl, hydroperoxyl, and superoxide radicals for wound healing. Materials Today Bio, 2025. 32: p. 101888.
25. Jung, H.H., et al., Wearable electrochemical sensors for real-time monitoring in diabetes mellitus and associated complications. 2024.
26. Harun-Or-Rashid, M., et al., Advances in electrochemical sensors for real-time glucose monitoring. Sensors & Diagnostics, 2024. 3(6): p. 893-913.
27. Yan, Y., et al., Bacterial cellulose as a promising biodegradable bioplastic for sustainability. Nature Communications, 2026.
28. Zahedi, A., R. Liyanapathirana, and K. Thiyagarajan, Biodegradable and renewable antennas for green iot sensors: a review. IEEE Access, 2024. 12: p. 189749-189775.
29. Gokhale, N.A., S.N. Joglekar, and S. Panda, Life cycle assessment of enzymatic and non-enzymatic electrochemical sensors: A comparative study using glucose oxidase and metal nano-catalysts. Journal of Cleaner Production, 2025. 522: p. 146327.
30. Ayoib, A., Hybrid nanomaterials in biosensors for advanced point-of-care diagnostics: DNA-, enzyme-, or immunosensor-based, for healthcare, in Hybrid-nanomaterials: Fabrication, characterization and applications. 2024, Springer. p. 123-153.
31. Fan, Y.-F., Z.-B. Guo, and G.-B. Ge, Enzyme-based biosensors and their applications. 2023, MDPI. p. 476.
32. Jiao, B., Applications of Electrochemical Biosensors across Medical, Environmental and Food Safety Fields. MedScien, 2025. 1(5).
33. Mousavian, Z., et al., Recent Advances in Development of Biosensors for Monitoring of Airborne Microorganisms. Iranian Journal of Biotechnology, 2024. 22(2): p. e3722.
34. Upadhaya, A., et al., Nanoparticle-Enabled Portable Biosensors for Early Detection and Monitoring of Non-Communicable Diseases: A Focus on Diabetes, Cardiovascular, and Cancer Diagnostics. Biosensors and Bioelectronics: X, 2025: p. 100675.
35. Huang, C.-W., et al., A review of biosensor for environmental monitoring: principle, application, and corresponding achievement of sustainable development goals. Bioengineered, 2023. 14(1): p. 58-80.
36. Bains, R.K., et al., Advances in the understanding and exploitation of carbohydrate-active enzymes. Current Opinion in Chemical Biology, 2024. 80: p. 102457.
37. Kaur, D., et al., Pectinases as promising green biocatalysts having broad-spectrum applications: Recent trends, scope, and relevance. Biotechnology and Applied Biochemistry, 2023. 70(5): p. 1663-1678.
38. Lzaod, S. and T. Dutta, Recent advances in the development of oxidoreductase-based biosensors for detection of phenolic antioxidants in food and beverages. ACS omega, 2022. 7(51): p. 47434-47448.
39. Wardman, J.F. and S.G. Withers, Carbohydrate-active enzyme (CAZyme) discovery and engineering via (Ultra) high-throughput screening. RSC Chemical Biology, 2024. 5(7): p. 595-616.
40. Patel, V.B., S. Chatterjee, and A.S. Dhoble, A review on pectinase properties, application in juice clarification, and membranes as immobilization support. Journal of Food Science, 2022. 87(8): p. 3338-3354.
41. Kurup, C.P. and M.U. Ahmed, Nanozymes towards personalized diagnostics: a recent progress in biosensing. Biosensors, 2023. 13(4): p. 461.
42. Abrantes-Coutinho, V.E., et al., Systematic review on lectin-based electrochemical biosensors for clinically relevant carbohydrates and glycoconjugates. Colloids and Surfaces B: Biointerfaces, 2021. 208: p. 112148.
43. Roman-Benn, A., et al., Pectin: An overview of sources, extraction and applications in food products, biomedical, pharmaceutical and environmental issues. Food Chemistry Advances, 2023. 2: p. 100192.
44. Hrmova, M. and J.G. Schwerdt, Molecular mechanisms of processive glycoside hydrolases underline catalytic pragmatism. Biochemical Society Transactions, 2023. 51(3): p. 1387-1403.
45. Cannac, N., et al., A QCM-D-based continuous assay for the study of the enzymatic degradation of insoluble calcium-polygalacturonate. Carbohydrate Polymers, 2025. 364: p. 123759.
46. Bykhovsky, D., Coherence time evaluation in indoor optical wireless communication channels. Sensors, 2020. 20(18): p. 5067.
47. Dong, Y., et al., Enzyme-responsive controlled-release materials for food preservation and crop protection-A review. International Journal of Biological Macromolecules, 2024. 254: p. 128051.
48. Abd El-Aziz, N.M., et al., RETRACTED ARTICLE: Enhancement of novel Endo-polygalacturonase expression in Rhodotorula mucilaginosa PY18: insights from mutagenesis and molecular docking. Microbial Cell Factories, 2023. 22(1): p. 252.
49. Gallemí, M., et al., Dual role of pectin methyl esterase activity in the regulation of plant cell wall biophysical properties. Frontiers in Plant Science, 2025. 16: p. 1612366.
50. Yadav, K., et al., Recent insights into microbial pectin lyases: a review. Process Biochemistry, 2023. 134: p. 199-217.
51. Mallick, P., et al., Revisiting interactions between polygalacturonases and polygalacturonase-inhibiting proteins and their effects on plant health: a review. Frontiers in Plant Science, 2025. 16: p. 1691420.
52. Stanek-Wandzel, N., et al., Evaluation of cellulase, pectinase, and hemicellulase effectiveness in extraction of phenolic compounds from grape pomace. International journal of molecular sciences, 2024. 25(24): p. 13538.
53. Li, P., et al., Improvement of optimum pH and specific activity of pectate lyase from Bacillus RN. 1 using loop replacement. Frontiers in Bioengineering and Biotechnology, 2023. 11: p. 1242123.
54. Chandel, V., et al., Current advancements in pectin: Extraction, properties and multifunctional applications. Foods, 2022. 11(17): p. 2683.
55. Rößling, A.-K., et al., Pectin methylesterase activity is required for RALF1 peptide signalling output. Elife, 2024. 13: p. RP96943.
56. Zhang, H. and F.-Q. Yang, A paper-based lateral flow strip assay based on enzyme-mediated pectin viscosity change for the determination of polygalacturonase activity. Microchemical Journal, 2023. 186: p. 108322.
57. Alqahtani, Y.S., et al., Production and purification of pectinase from Bacillus subtilis 15A-B92 and its biotechnological applications. Molecules, 2022. 27(13): p. 4195.
58. Pathan, S.U., et al., Enzymes as indispensable markers in disease diagnosis. Bioanalysis, 2024. 16(10): p. 485-497.
59. Singh, R., et al., A review on recent trends and future developments in electrochemical sensing. ACS omega, 2024. 9(7): p. 7336-7356.
60. Naresh, V. and N. Lee, A review on biosensors and recent development of nanostructured materials-enabled biosensors. Sensors, 2021. 21(4): p. 1109.
61. Chen, C. and J. Wang, Optical biosensors: An exhaustive and comprehensive review. Analyst, 2020. 145(5): p. 1605-1628.
62. Zhou, J., et al., Recent advances in design and application of nanomaterials-based colorimetric biosensors for agri-food safety analysis. ACS omega, 2023. 8(49): p. 46346-46361.
63. Pohanka, M., Piezoelectric chemosensors and biosensors in medical diagnostics. Biosensors, 2025. 15(3): p. 197.

64. Skládal, P., Piezoelectric biosensors: shedding light on principles and applications. Microchimica Acta, 2024. 191(4): p. 184.
65. Sonowal, K., P.P. Borthakur, and K. Pathak, Advances in Enzyme-Based Biosensors: Emerging Trends and Applications. Engineering Proceedings, 2025. 106(1): p. 5.
66. Sadani, K., et al., Enzymatic optical biosensors for healthcare applications. Biosensors and Bioelectronics: X, 2022. 12: p. 100278.
67. Majer-Baranyi, K., A. Székács, and N. Adányi, Application of electrochemical biosensors for determination of food spoilage. Biosensors, 2023. 13(4): p. 456.
68. Li, D., et al., Ripening induced degradation of pectin and cellulose affects the far infrared drying kinetics of mangoes. Carbohydrate Polymers, 2022. 291: p. 119582.
69. Navarro-López, D.E., et al., Nanocatalytic performance of pectinase immobilized over in situ prepared magnetic nanoparticles. Heliyon, 2023. 9(8).
70. Said, N.S. and W.Y. Lee, Pectin-based active and smart film packaging: a comprehensive review of recent advancements in antimicrobial, antioxidant, and smart colorimetric systems for enhanced food preservation. Molecules, 2025. 30(5): p. 1144.
71. Liu, Y., et al., A highly sensitive, accurate, and stable method for measuring pectin depolymerase activity. Food Chemistry, 2025. 463: p. 141229.
72. Nazari-Vanani, R. and M. Negahdary, Recent advances in electrochemical aptasensors and genosensors for the detection of pathogens. Environmental Research, 2024. 243: p. 117850.
73. Gao, S., et al., Magnetic nanoparticle-based immunosensors and aptasensors for mycotoxin detection in foodstuffs: An update. Comprehensive Reviews in Food Science and Food Safety, 2024. 23(1): p. e13266.
74. Guan, Y., et al., Recent advances in microbial whole-cell biosensors for detecting food contaminants: a review. Food Control, 2025: p. 111674.
75. Bergman, G.Ö., et al., Engineering chimeric signaling proteins for microbial whole-cell biosensors: from design to deployment. Trends in Biotechnology, 2025.
76. Feng, Y., et al., Advancing food safety surveillance: rapid and sensitive biosensing technologies for foodborne pathogenic bacteria. Foods, 2025. 14(15): p. 2654.
77. Basu, S. and G. Bisker, Near-Infrared Fluorescent Single-Walled Carbon Nanotubes for Biosensing. Small, 2025. 21(26): p. 2502542.
78. Wang, F., et al., Application of immobilized enzymes in juice clarification. Foods, 2023. 12(23): p. 4258.
79. Hasanah, U., et al., Construction of a hydrogel pectin-based triglyceride optical biosensor with immobilized lipase enzymes. Biosensors, 2019. 9(4): p. 135.
80. Zhao, M., et al., Advances in Pectinase Engineering for Food Bioprocessing: Novel Sources, Mechanisms, and Optimization Strategies. Journal of Agricultural and Food Chemistry, 2025. 73(37): p. 23078-23097.
81. Mustafa, F., S. Liebich, and S. Andreescu, Nanoparticle-based amplification for sensitive detection of β-galactosidase activity in fruits. Analytica Chimica Acta, 2021. 1186: p. 339129.
82. Zhao, Z., et al., Recent advances in MXene-based electrochemical sensors. Biosensors, 2025. 15(2): p. 107.
83. Ali, M., et al., Unlocking the Potential of MXene-Based Electrochemical Biosensors: A Review of Biofunctionalization Strategies and Biosensing Principles. Advanced Materials Technologies, 2026. 11(12): p. e02120.
84. Fakhr, M.H., et al., Recent advances in wearable electrochemical biosensors towards technological and material aspects. Biosensors and Bioelectronics: X, 2024. 19: p. 100503.
85. Zhu, S., et al., AI-assisted molecular biosensors: design strategies for wearable and real-time monitoring. International Journal of Molecular Sciences, 2026. 27(7): p. 3305.
86. Abdel-Mageed, H.M., Frontiers in nanoparticles redefining enzyme immobilization: a review addressing challenges, innovations, and unlocking sustainable future potentials. Micro and Nano Systems Letters, 2025. 13(1): p. 7.
87. Baruah, A., et al., Biomedical applications of graphene-based nanomaterials: recent progress, challenges, and prospects in highly sensitive biosensors. Discover Nano, 2024. 19(1): p. 103.
88. Zhang, J., et al., Emerging biosensors integrated with microfluidic devices: a promising analytical tool for on-site detection of mycotoxins. npj Science of Food, 2025. 9(1): p. 84.
89. Weston, M., et al., Anthocyanin-based sensors derived from food waste as an active use-by date indicator for milk. Food Chemistry, 2020. 326: p. 127017.
90. Bhatlawande, A.R., et al., Unlocking the future of smart food packaging: biosensors, IoT, and nano materials: AR Bhatlawande et al. Food Science and Biotechnology, 2024. 33(5): p. 1075-1091.
91. Meliana, C., et al., Biosensor in smart food traceability system for food safety and security. Bioengineered, 2024. 15(1): p. 2310908.
92. Ayenimo, J.G. and S.B. Adeloju, Amperometric detection of glucose in fruit juices with polypyrrole-based biosensor with an integrated permselective layer for exclusion of interferences. Food chemistry, 2017. 229: p. 127-135.
93. Lipińska, W., K. Grochowska, and K. Siuzdak, Enzyme immobilization on gold nanoparticles for electrochemical glucose biosensors. Nanomaterials, 2021. 11(5): p. 1156.
94. Abdullah, A., et al., Microfluidic based impedance biosensor for pathogens detection in food products. Electrophoresis, 2019. 40(4): p. 508-520.
95. Wang, B., D. Huang, and Z. Weng, Recent advances in polymer-based biosensors for food safety detection. Polymers, 2023. 15(15): p. 3253.
96. Bucur, B., et al., Advances in enzyme-based biosensors for pesticide detection. Biosensors, 2018. 8(2): p. 27.
97. Valenzuela-Amaro, H.M., et al., Emerging applications of nanobiosensors in pathogen detection in water and food. Biosensors, 2023. 13(10): p. 922.
98. Gan, Q., et al., Advancing lignocellulosic conversion though biosensor-enabled metabolic engineering. Green Chemistry, 2025. 27(33): p. 9862-9873.
99. Salek Maghsoudi, A., et al., Recent advances in nanotechnology-based biosensors development for detection of arsenic, lead, mercury, and cadmium. International Journal of Nanomedicine, 2021: p. 803-832.
100. Pontius, K., et al., Automated electrochemical glucose biosensor platform as an efficient tool toward on-line fermentation monitoring: novel application approaches and insights. Frontiers in Bioengineering and Biotechnology, 2020. 8: p. 436.
101. Yang, L., et al., A biosensor based on oriented immobilization of an engineered l-glutamate oxidase on a screen-printed microchip for detection of l-glutamate in fermentation processes. Food Chemistry, 2023. 405: p. 134792.
102. Waly, Y., et al., Evolution of Biosensors and Current State-of-the-Art Applications in Diabetes Control. Biosensors, 2026. 16(1): p. 39.
103. Parihar, M., et al., Point-of-care biosensors for infectious disease diagnosis: recent updates and prospects. RSC advances, 2025. 15(36): p. 29267-29283.
104. Ondevilla, N.A.P., et al., A point-of-care electrochemical biosensor for the rapid and sensitive detection of biomarkers in murine models with LPS-induced sepsis. Biosensors and Bioelectronics, 2024. 254: p. 116202.
105. Han, Q., et al., Graphene biodevices for early disease diagnosis based on biomarker detection. ACS sensors, 2021. 6(11): p. 3841-3881.
106. GeGen, S., et al., Advances in aptamer-based electrochemical biosensors for disease diagnosis: integration of DNA and nanomaterials. Nanoscale Horizons, 2025. 10(11): p. 2668-2687.
107. Ansari, S.A., et al., Recent updates on stabilization of recombinant enzymes via nanotechnology-based approaches. Discover Food, 2024. 4(1): p. 159.
108. Wang, J., Y. Zeng, and W. Wang, Recent Advances in Enzyme Activity Assay Methods: A Systematic Review of Emerging Technologies and Applications. Analytical Chemistry, 2026.
109. Abdullahi, H.Y., et al., Spotlight on pectinase: a comprehensive review of large-scale production strategies. Critical Reviews in Biotechnology, 2026: p. 1-21.
110. Rahimnejad, M., R. Abd Alsaheb, and M. Atyia, Current developments in biosensors for monitoring environmental quality: A critical review. 2025.
111. Sivakumar, S., et al., Bioengineered Nano-sorbents: Microbial Allies in Pollutant Sequestration, in Nano-microbiology for Sustainable Development. 2025, Springer. p. 331-372.
112. Yusuf, M. and M. Shahid, Biotechnology Approaches in Textile Technology: Progress and Trends. 2025: CRC Press.

113. Malzacher, S., et al., The STRENDA Biocatalysis Guidelines for cataloguing metadata. Nature Catalysis, 2024. 7(12): p. 1245-1249.
114. Zahra, H., et al., From nature to industry: harnessing the power of pectinase towards potential biotechnological applications. Int. J. Biol. Biotech., 2024. 21(1): p. 17-35.
115. Mor, R., A review on development of enzymatic biosensors for industrial applications. World journal of advanced Research and Reviews, 2024. 23(1): p. 2582-2590.

Supporting Information

Stimuli-Response in Organic Cocrystals with Different Donor-Acceptors

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Crystal growth and preparation of cocrystals

Acenaphthylene (AE), dithieno[3,2-b:2',3'-d]thiophene (DTT), and 3-aminopyridine (3-AP) were used as different donor molecules, while tetracyanobenzene (TCNB) served as the common acceptor, to prepare organic cocrystals in various solvents. Additionally, a mixture of AE (4.5 mg, 0.03 mmol), DTT (5.88 mg, 0.03 mmol), and 3-AP (2.82 mg, 0.03 mmol) was combined with TCNB (5.34 mg, 0.03 mmol) and gradually dissolved in 5 mL of tetrahydrofuran (THF), ethyl acetate (EA), or dichloromethane (DCM). The cocrystals were then prepared in a 1:1 stoichiometric ratio of donor to acceptor using the solvent evaporation method. Specifically, the solvent evaporation method usually dissolves a certain proportion of the reaction mixture solution in a bottle and then stores it in a dark environment and at room temperature. The solute gradually reaches a saturated state in the solution, and forms cocrystal nuclei driven by intermolecular interactions and gradually precipitates out after a few days. This method usually requires donor and acceptor molecules to have similar solubility in the same solvent and it is highly dependent on factors such as solvent, concentration, temperature, and other external conditions.

However, for the crystal structure analyses and more characterization, we used powder X-ray diffraction (PXRD) and optical microscope (OM). For the studies and determination of photophysical chemical properties, we used solid-state samples of the AETC, DTTC and 3-ATC cocrystals with different instrument measurements such as UV-vis, photoluminescence (PL), thermal gravimetric analysis (TGA), differential scanning calorimetry (DSC) and Fourier-transform infrared (FTIR).

Table S1 The single-crystal data of AETC, DTTC and 3-ATC cocrystals.

Chemical formula	**$C_{22}H_{10}N_4$**	**$C_{18}H_6N_4S_3$**	**$C_{15}H_8N_6$**

CCDC	2287450	2287435	2347457
Formation weight	330.34	374.45	272.27
Temperature /K	160/K	160/K	160 K
Wavelength	1.54184	1.54184	1.54184
Space group	P-1	P-1	C2/c
Crystal system	triclinic	triclinic	monoclinic
a/Å	6.7303(3)	7.2203(2)	7.2422(1)
b/Å	8.0525(3)	9.1337((2)	15.4771(1)
c/Å	15.2393(5)	12.6626(3)	11.6557(1)
α/°	94.320(3)	92.056(2)	90
β/°	99.821(3)	94.846(2)	92.677(1)
γ/°	97.783(3)	95.128(2)	90
Volume/ Å3	802.20 (5)	827.97(5)	1305.04(2)
Z	2	2	4
ρ_{calc}g/cm^3	1.368	1.502	1.386
μ /mm−1	0.667	4.161	0.733
F(000)	340.0	380.0	560.0
R_{int}	0.0677	0.0462	0.0291
Goof	1.072	1.061	1.115
Final R indexes [I>=2σ (I)]	wR_1 = 0.0677, wR_2 = 0.2146	wR_1 = 0.0462, wR_2 = 0.1390	wR1 = 0.0291, wR2 = 0.0824

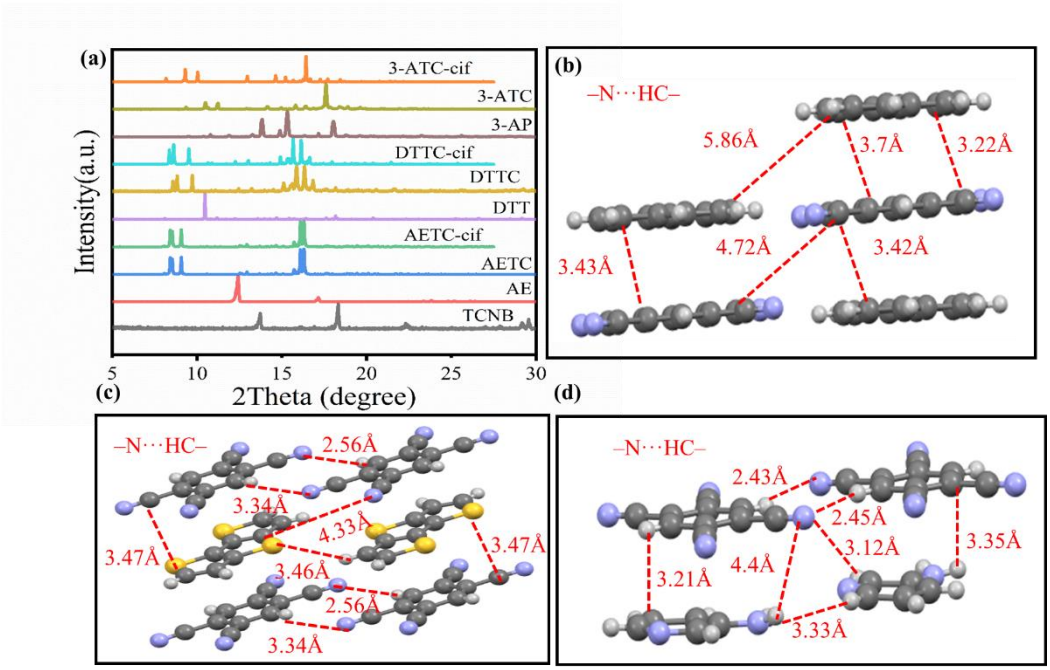

Fig. S1, a) PXRD, and b-d the distance in the π-π direction of AETC, DTTC and 3-ATC organic cocrystal.

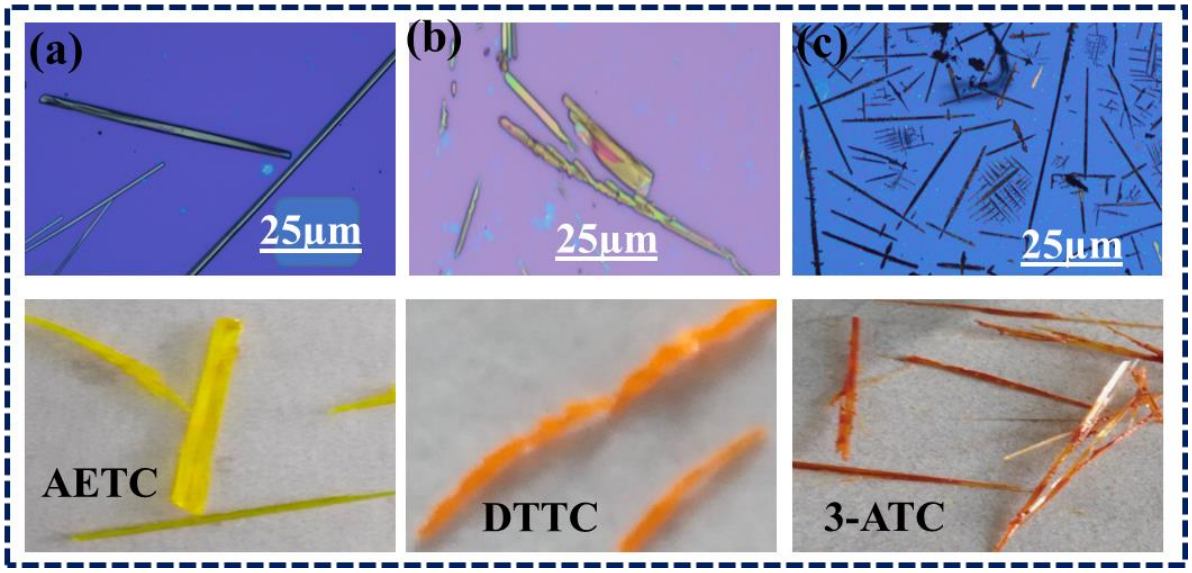

Fig. S2, a-c) The OM, images of AETC, DTTC and 3-ATC organic cocrystal shown 2D for AETC, 1D DTTC and 3-ATC organic cocrystal.

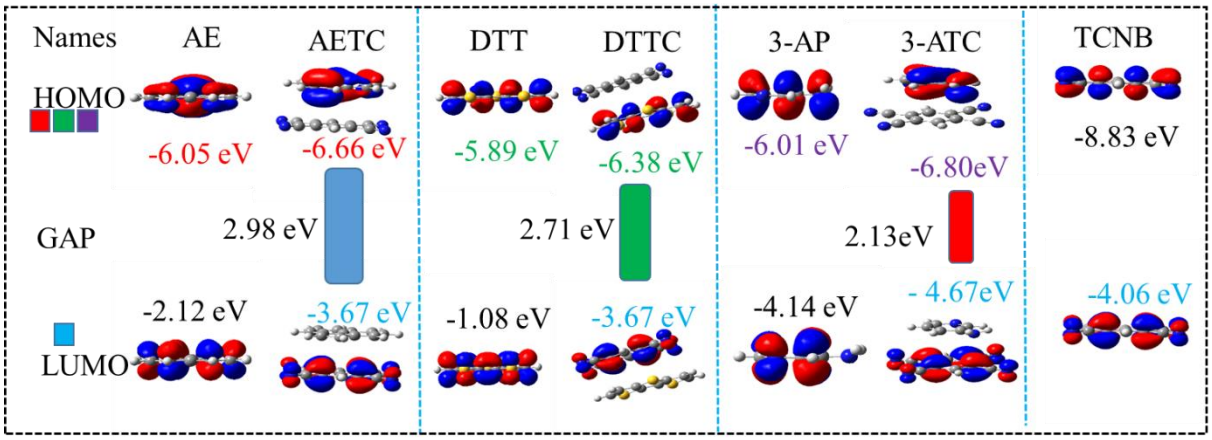

Fig. S3), the band gap of AETC, DTTC and 3-ATC organic cocrystals and host materials AE,DTT and 3-AP.

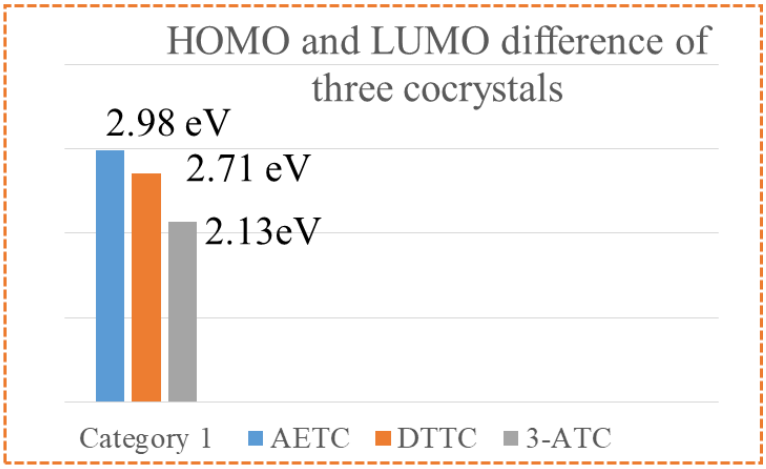

Fig. S4), the band gap of AETC, DTTC and 3-ATC organic cocrystals.

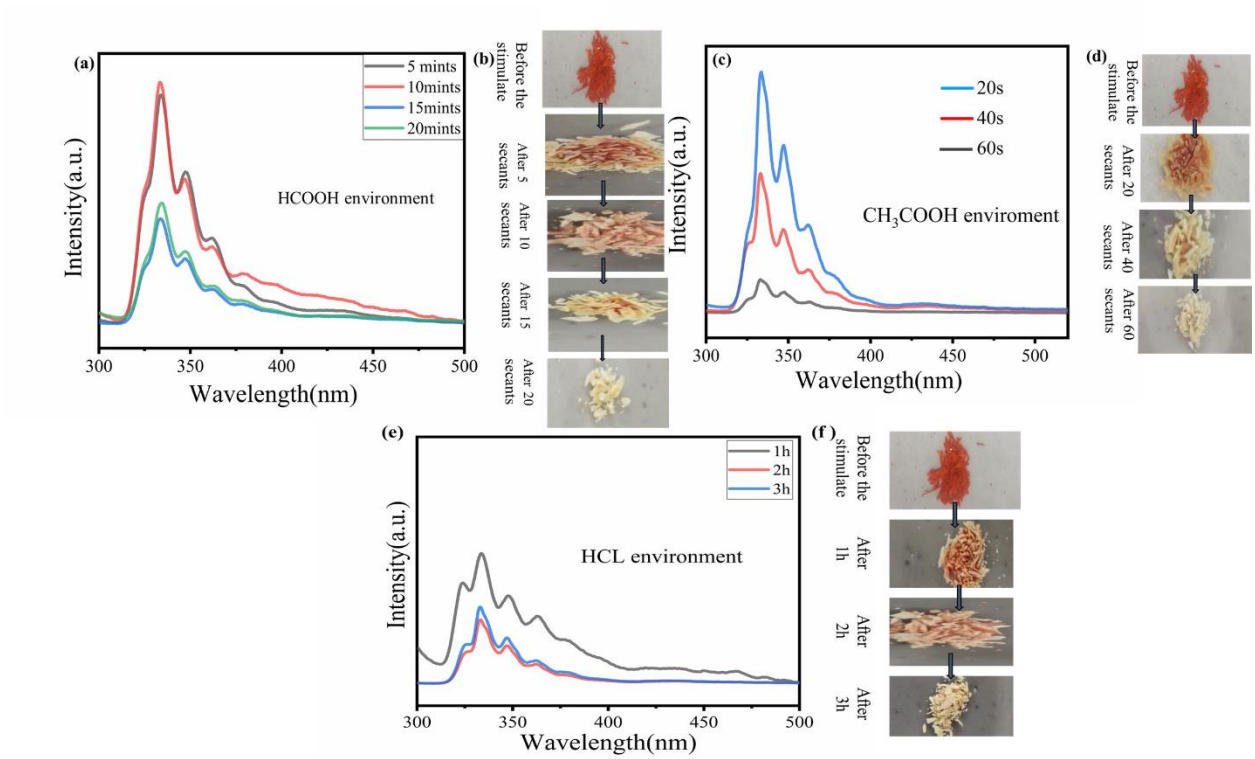

Fig. S5. a-b) Intensities of fluorescence and color change in formic acid environment,c-d) in acetic acid environment, e-f) and in hydrochloric acid environment.

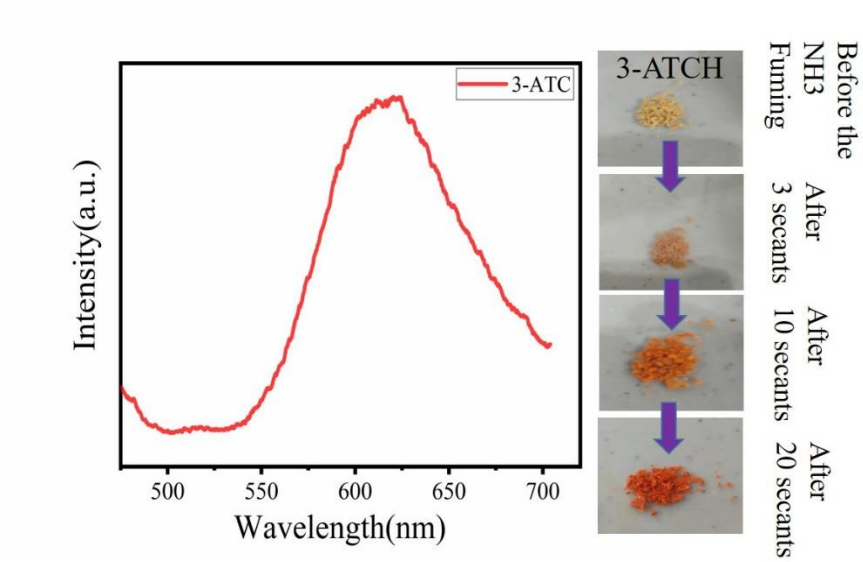

Fig. S6. Intensities of fluorescence and color recycal in NH_3 environment.