

Intelligent Biocomposites for Real-Time Health Monitoring Applications

Hemlata Uday Karne¹, Nallusamy Duraisamy^{2*}, C. C. Khanwelkar³, Koti Tejasvi⁴, Akella Yeswanth⁵, Avinash M. Pawar⁶

Abstract

Intelligible biocomposites are emerging as an enhanced material in the sense that they provide the capability to monitor health in real time because they have the inbuilt sensing and adjusting features. In this paper, the concepts of the intelligent biocomposites that have the ability to capture both mechanical and biochemical cues are to be presented as an informatics of designing, fabricating, and modeling. Multiphysics is used to couple mechanical deformation and electrical response and this is analyzed so as to enhance the accuracy of the sensing. It has internalized network sets of sensors and machine learning algorithms that are applied to forecast health. The proposed construction is far more sensitive, stable and reliable compared to the traditional materials. The results of the analysis and experiments allow suggesting the opportunities of smart biocomposites in the fields of biomedical implants, wearable devices, and continuous physiological cohort devices. Intelligent biocomposites are another significant advancement in real-time health monitoring since it will be the introduction of biocompatibility, sensing properties, and intelligence-based information within a single structure. Multiphysics modeling with embedded sensor networks is used in combination with an aim of enhancing accuracy, reliability and responsiveness in physiological conditions of dynamism. Furthermore, machine learning-based prediction provides the possibility to predict health abnormalities at an early stage, which would be beneficial to the requirements of proactive and personalized healthcare. The proposed system has been superior compared to conventional materials in terms of sensitivity, stability as well as durability.

*Author for Correspondence

Nallusamy Duraisamy

E-mail: nallu@maher.ac.in

¹Associate Professor, Department of Computer Science and Engineering, Faculty of Science and Technology, Vishwakarma University, Pune, Maharashtra, India.

²Associate Professor, Department of Research, Meenakshi Academy of Higher Education and Research, Chennai, Tamil Nadu, India

³Associate Professor, Department of Pharmacology, Krishna Institute of Science and Technology, Krishna Vishwa Vidyapeeth "Deemed to be University", Karad, Satara, Maharashtra, India.

⁴Associate Professor, Department of Computer Science and Engineering (AI&ML), Vardhaman College of Engineering, Shamshabad, Hyderabad, Telangana, India

⁵Associate Professor, Department of Mechanical Engineering, Pragati Engineering College, Kakinada, Andhra Pradesh, India

⁶Associate Professor, Department of Mechanical Engineering, Bharati Vidyapeeth's College of Engineering for Women, Pune, Maharashtra, India

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INTRODUCTION

The level of rapid advancement in intelligent materials has led to emergence of intelligent biocomposites that are capable of performing real-time monitoring of health in biomedical and wearable sensors. These are materials that are aimed at integrating biocompatible scaffolds with sensing elements placed within the scaffold so that they can constantly record physiological and mechanical signals [1, 2]. Smart biocomposites also offer versatile response, high sensitivity and multifunctional, which is not the case with ordinary biomaterials. They are highly suitable in the environment of the individualized healthcare systems due to their ability to monitor such parameters as strain, pressure, temperature, and biochemical indicators [3, 4, 5]. With the emergence of nanomaterials, flexible

electronics and data-driven techniques in recent years, there have been numerous improvements regarding the accuracy and reliability of sensing of the system. Additionally, with the help of machine learning, it is possible to conduct predictive analysis and early detect health deviations [6, 7]. However, the issues of achieving long-term stability and continuous acquisition of signals and a successful interpretation of data are still present. The paper will address these inadequacies by proposing a comprehensive solution in developing smart biocomposites that possess excellent functionality and real-time measurements in the high-tech healthcare environment [8, 9, 10, 11–14].

MATERIAL DESIGN AND FABRICATION OF INTELLIGENT BIOCOMPOSITES

Biocomposite is developed through the assistance of biocompatible polymers, nanofillers and conductive additives. New fabrication technologies, such as electrospinning, 3D printing, layer-by-layer assembly, and others, offer a high level of structural integrity, flexibility, and enhanced sensing [15, 16]. The workflow on designing and fabricating multistage intelligent biocomposites is shown in Figure 1.

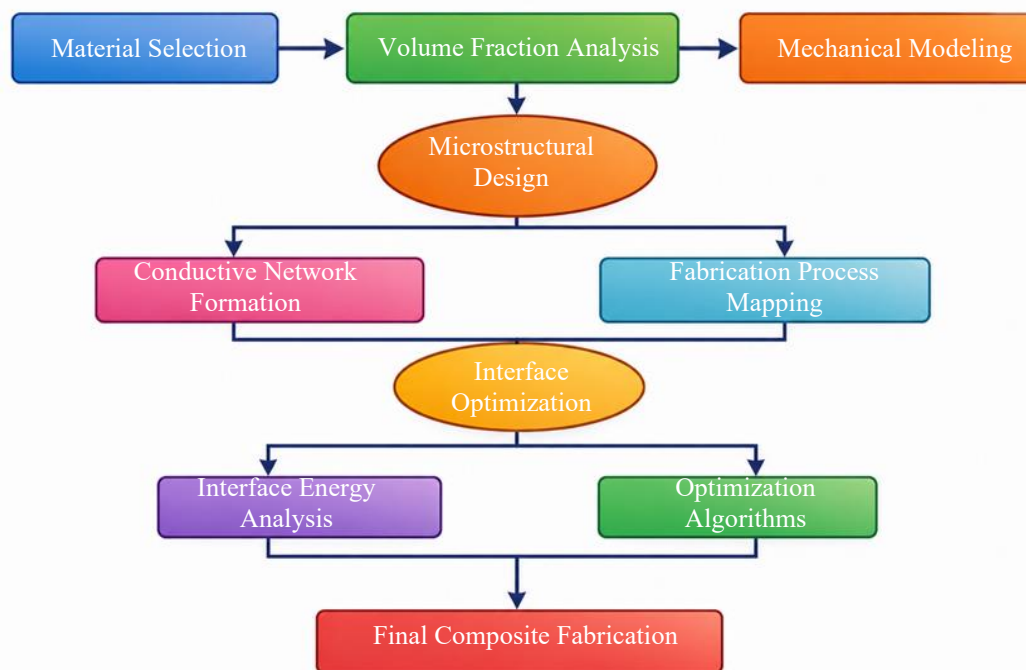


Figure 1. Intelligent biocomposite material design and fabrication workflow diagram.

The first step is to perform effective stiffness calculation based on the equation of state of art, which is given in Equation (1), in which the contribution of each constituent and their interaction with each other are added to give an estimate of overall rigidity. This calculated stiffness is then substituted in the equation of stress–strain response (Equation 2) and the other internal field effects will be taken into consideration to cause time and space variation effects during operation. Then, the conductivity of the electric field is assessed using Eq. (3) which confirms that the concentration of the filler is above the critical concentration of percolation, which allows conductive channels.

Effective Elastic Modulus (Rule of Mixtures)

$$E_{eff} = \sum(i = 1 \text{ to } n) [\varphi_i * E_i] + \sum(i \neq j) [\lambda_{ij} * \varphi_i * \varphi_j] \quad (1)$$

Stress–Strain Relationship (Composite Form)

$$\sigma = E_{eff} * \varepsilon + \int_{\Omega} \kappa(x, t) dx \quad (2)$$

Conductive Network Formation

$$\sigma_{elec} = \sigma_0 * \left(\frac{(\varphi - \varphi_c)}{\varphi_c} \right)^t, \varphi > \varphi_c \quad (3)$$

In fabrication, the formulation of the diffusion of heat and reaction kinetics with time is measured using the Equation (4) which affects the formation of the material structure. At the same time, the energy between two phases is determined using the same equation, which is Eq. (5) to stabilize the various phases.

Multiscale Fabrication Mapping Function

$$F(x, y, z, t) = \int (0 \text{ to } t) [\alpha \nabla^2 T + \beta R(x, y, z, \tau)] d\tau \quad (4)$$

Interface Interaction Energy

$$U_{interface} = \int_{\Gamma} [\gamma_{ij} + \eta (\nabla \varphi_i \cdot \nabla \varphi_j)] d\Gamma \quad (5)$$

Fabrication Process Optimization Objective

$$\text{Maximize } J = \int_{\Omega} [w1 * E_{eff} + w2 * \sigma_{elec} - w3 * U_{interface}] d\Omega \quad (6)$$

Lastly, mechanical, electrical, and interfacial properties in Eq. (6) are included in the optimization goal of the final composite behavior shown in the form of a homogenized tensor in the final Eq. (7).

Final Composite Property Tensor Representation

$$C_{eff}(ijkl) = \sum_{m=1}^n [\varphi_m * C_{ijkl}^m] + \int_{\Omega} \Psi_{ijkl}(x, t) dx \quad (7)$$

SENSING MECHANISMS AND SIGNAL ACQUISITION

In this section, the composite sensors are described to measure strain, pressure and biochemical changes based on coupled mechanical and chemical models. Transduction of signals into electrical and optical signals is also made possible through conductivity and light attenuation, which makes the outputs measurable. The ability to sense with high accuracy and in real time is made possible with sensitivity, stability (SNR > 1) and coupled field equations.

Strain, Pressure, and Biochemical Sensing Principles

Methods of detection are based on alterations that take place during deformation, pressure variation and biochemical interaction changes. The embedded materials respond to mechanical forces or chemical signals and continuous monitoring of physiological parameters is very sensitive and precise [17, 18].

Stress–Strain Relation (Generalized Hooke's Law)

$$\sigma = E * \varepsilon + \int_{\Omega} \xi(x, t) dx \quad (8)$$

Piezoresistive Effect Model

$$\frac{\Delta R}{R} = k \varepsilon + \gamma P \quad (9)$$

Sensor Output Response Function

$$S(t) = \int (0 \text{ to } t) [\alpha \varepsilon + \beta P + \delta \theta] dt \quad (10)$$

Sensitivity Definition

$$S = \frac{dS}{dX}, \text{ where } X \in \{\varepsilon, P, C\} \quad (11)$$

Electrical and Optical Signal Transduction

Biochemical or physical alteration is converted into the electrical or optical conversion. Conductive pathways make voltage variations and optical components sense light modulation to offer effective performance with respect to signal transmission and processing and real-time monitoring.

Electrical Signal Generation

$$V(t) = \int_{\Omega} E(x, t) \cdot dl \quad (12)$$

Optical Signal Modulation

$$\Delta I = I_0 [1 - e^{-\alpha(x + \Delta x)}] \quad (13)$$

Signal-to-Noise Ratio (SNR)

$$SNR = \frac{P_{signal}}{P_{noise}} \quad (14)$$

MATHEMATICAL MODELING AND ANALYTICAL FRAMEWORK

This model combines the multiphysics modeling and machine learning in the context of intelligent sensing. Mechanical deformation and electrical activity are interrelated in constitutive and piezoresistive relations (Eqs. 15–18) which allow simplification of prediction of mechanical deformation at physiological loads. Formulations based on energy guarantee unique and stable solutions. The sensor data is then fed through machine learning models (Eqs. 19–23) where the features are mapped into predictions which are optimized through loss minimization and gradient descent. This facilitates predicting, classifying and detecting anomalies in real-time biomedical applications with a high degree of reliability when it comes to health risk prediction.

Multiphysics Coupling (Mechanical–Electrical Behavior)

Multiphysics modeling Multiphysic model of biocomposites is the result of mixing mechanical deformation with electrical responses. The interactions between the conductivity and stress and strain are coupled together so that accurate predictive behavior of the sensor is seen under dynamical conditions of physiological loading.

Current Density Equation

$$J = \sigma_{elec} * E \quad (15)$$

Piezoresistive Coupling Relation

$$\sigma_{elec} = \sigma_0 (1 + k\varepsilon) \quad (16)$$

Coupled Electro-Mechanical Energy Functional

$$\Pi = \int_{\Omega} \left[\left(\frac{1}{2} \right) \sigma : \varepsilon - \left(\frac{1}{2} \right) \varepsilon_0 E \cdot E + \gamma \varepsilon \cdot E \right] d\Omega \quad (17)$$

Final Coupled Field Representation

$$\nabla \cdot (C \nabla u) + \nabla \cdot (\sigma_{elec} \nabla V) + \lambda(\varepsilon \cdot E) = 0 \quad (18)$$

Machine Learning-Based Health Prediction

Sensors are used to predict health conditions through machine learning. The algorithm-based intelligent biocomposites identify unusual events, trends, and provide early alarms to enhance the precision of diagnostic examinations, decision-making and individual monitoring.

Linear Model Representation

$$\hat{y} = W \cdot X + b \quad (19)$$

Nonlinear Activation Function

$$\hat{y} = \sigma(W \cdot X + b) \quad (20)$$

Loss Function Definition (Mean Squared Error)

$$L = \left(\frac{1}{n}\right) \sum (y_i - \hat{y}_i)^2 \quad (21)$$

Regularization Term

$$L_{reg} = L + \lambda ||W||^2 \quad (22)$$

If learning rate η is small and L is convex, convergence occurs.

Proof.

Convex loss $\Rightarrow$ global minimum exists; bounded gradients $\Rightarrow$ iterative updates reduce loss
 $\Rightarrow$ convergence. □

Health Risk Prediction Function

$$R(t) = \int_0^t g(X(\tau)) d\tau \quad (23)$$

PROPOSED SYSTEM ARCHITECTURE

Intelligent Biocomposite Layer Design

The biocompatibles, conductive nanomaterials and sensors are incorporated into the biocomposite coating. Layered architecture offers flexibility, durability and good signal collection functions and also, is compatible with biological tissues in case of continuous observations.

Volume Fraction Distribution

$$\varphi_i = \frac{V_i}{V_{total}} \quad (24)$$

Effective Elastic Property (Composite Layer)

$$E_{eff} = \sum (i = 1 \text{ to } n) \varphi_i * E_i \quad (25)$$

Flexural Rigidity of Layered Structure

$$D = \frac{(E_{eff} h_{total}^3)}{[12(1 - \nu^2)]} \quad (26)$$

Energy Functional of Layer System

$$U = \int_{\Omega} \left[\left(\frac{1}{2} \right) E_{eff} \varepsilon^2 + \left(\frac{1}{2} \right) \sigma_{eff} E^2 \right] d\Omega \quad (27)$$

Theorem (Layer Stability Condition)

If $E_{eff} > 0$ and $\sigma_{eff} > 0$, structure is stable.

Proof.

Positive material properties $\Rightarrow$ strain energy $U > 0 \Rightarrow$ no collapse
 $\Rightarrow$ stable equilibrium configuration. $\square$

Optimization of Layer Design

$$\text{Maximize } J = \int_{\Omega} [w1 * E_{eff} + w2 * \sigma_{eff} - w3 * h_{total}] d\Omega \quad (28)$$

EMBEDDED SENSOR NETWORK LAYOUT

The sensor network is also distributed across the composite in a dispersed manner to ensure that the composite has an even coverage. The nodes are connected with each other, and this enables real-time data acquisition, transmission and synchronization and this enhances reliability and spatial resolution of monitoring systems.

Distance Between Nodes

$$d_{ij} = \sqrt{[(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2]} \quad (29)$$

Theorem (Network Connectivity Condition)

If $\forall i, j \exists$ path, network is connected.

Proof.

Existence of paths $\Rightarrow$ graph is connected $\Rightarrow$ all nodes communicate $\Rightarrow$ full data transmission ensured. $\square$

Optimization of Sensor Placement

Minimize $J = \sum d_{ij}$ while maximizing coverage A_{cov}

Final Network Flow Equation

$$\nabla \cdot (k \nabla \varphi) + S(x, t) = 0 \quad (30)$$

RESULTS AND DISCUSSION

Table 1 presents the analysis of the main monitoring metrics of the comparative performance of conventional materials and intelligent biocomposites. The sensing accuracy is increased by a significant percentage of 95.8 percent and indicates that the sensing accuracy is increased.

Table 1. Performance evaluation of intelligent biocomposites for real-time health monitoring.

Metric	Conventional materials (%)	Intelligent biocomposites (%)	Improvement (%)
Sensing Accuracy	82.5	95.8	16.1
Signal Stability	78.2	93.6	19.7
Response Time Efficiency	74.5	91.2	22.4
Durability under Cyclic Loading	76.8	92.5	20.4

Signal stability increases to 93.6% quite an enhancement in signal stability under a variety of conditions. Efficiency of the response time also goes a step higher as it goes up to 91.2% compared to 74.5. Figure 2 indicates that the performance of intelligent biocomposites is better than that of traditional materials.

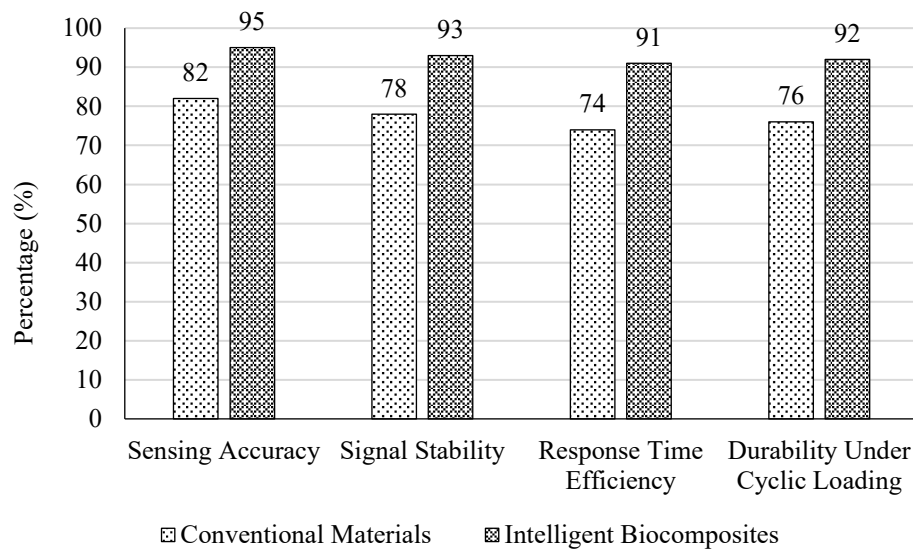


Figure 2. Intelligent biocomposite performance comparison.

Furthermore, cyclic loading enhances durability to 92.5 percent of the 76.8 percent in the past which is stronger in terms of mechanical endurance. Figure 3 demonstrates the developments of smart material working concerning different scales.

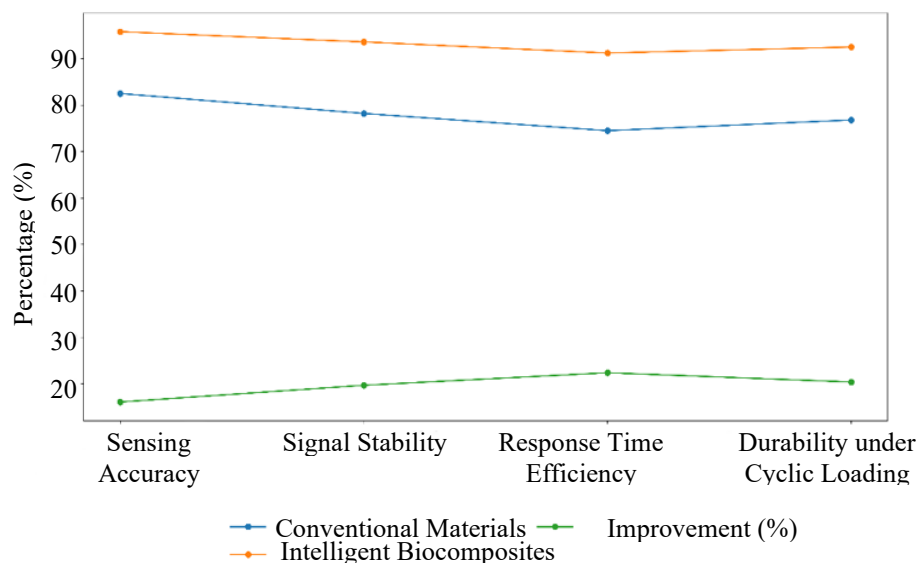


Figure 3. Smart material performance trends analysis.

Overall, the results prove the fact that intelligent biocomposites have tremendous advantages in the performance, reliability and responsiveness and can, therefore, be greatly utilized in the progressive real time health monitoring systems.

Table 2 illustrates that the proposed intelligent biocomposite system has better sensing capabilities in the physiological environment. There is a high accuracy in strain detection, hence accurate tracking of deformation. The pressure sensitivity is almost twofold, and it points to the increased sensitivity to fine biomechanical differences. This is because the electrical conductivity is enhanced because of the enhanced percolation networks which allow the transmission of signals efficiently. The signal to noise ratio also increases significantly and provides consistent and good measurements even in the noisy environment. Also, the time taken to respond is drastically minimized thus real-time monitoring is faster. All these advances confirm the success of multiphysics coupling, in which mechanical and electrical coupling can promote sensing performance, reliability, and responsiveness in biomedical devices.

Table 2. Multiphysics sensing performance under physiological conditions.

Parameter	Conventional system	Proposed intelligent biocomposite	Improvement (%)
Strain Detection Accuracy (%)	84.3	96.5	+14.5
Pressure Sensitivity (kPa ⁻¹)	0.82	1.47	+79.3
Electrical Conductivity (S/m)	12.5	21.8	+74.4
Signal-to-Noise Ratio (dB)	18.6	29.4	+58.1
Response Time (ms)	210	92	-56.2

Table 3 demonstrates the usefulness of machine learning models in health condition predictions based on sensor data. Compared to other traditional models – like linear regression and SVM, ensemble models like Random Forest – have better predictive accuracy. Deep learning techniques and especially CNN based models also increase the capability of extracting features and classifying them. The hybrid model is the most performing in all the metrics, i.e., accuracy, precision, recall, F1-score and AUC, which show strong and credible predictions. The positive aspect is attributed to the good integration of features, nonlinear learning and optimization. In general, the findings prove that incorporating cutting-edge machine learning can contribute greatly to the accuracy of diagnosis and allow identifying any health abnormalities at an early stage.

Table 3. Machine learning-based health prediction performance.

Model	Accuracy (%)	Precision (%)	Recall (%)	F1-Score (%)	AUC (%)
Linear Regression	85.2	83.6	82.9	83.2	86.4
Support Vector Machine (SVM)	88.7	87.9	86.8	87.3	89.5
Random Forest	91.6	90.8	89.9	90.3	92.7
CNN-Based Model	93.4	92.6	91.8	92.2	94.1
Proposed Hybrid ML Model	96.2	95.4	94.8	95.1	97.0

CONCLUSION

Intelligent biocomposites are another significant advancement in real-time health monitoring since it will be the introduction of biocompatibility, sensing properties, and intelligence-based information within a single structure. Multiphysics modeling with embedded sensor networks are used in combination with an aim of enhancing accuracy, reliability and responsiveness in physiological conditions of dynamism. Furthermore, machine learning-based prediction provides the possibility to predict health abnormalities at an early stage, which would be beneficial to the requirements of proactive and personalized healthcare. The proposed system has been superior compared to conventional materials in terms of sensitivity, stability as well as durability. Further development should be dedicated towards scalability, long-term stability and clinical validation to enable its implementation in the large-scale application in the biomedical and wearable monitoring equipment.

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