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Article

Development and Characterization of HDPE Composite Floating Photovoltaic Structures: Performance Optimization and Reliability under Multi-Environmental Loading

Priyanka N. Jadhav Mhaske[1], Prajitsen G. Damle[2]

[1]Department of Mechanical Engineering, KBCNMU, Jalgaon (M.S) India Maharashtra, India
[2]Mechanical Engineering, SSBT's COET, Bambhori, Jalgaon (M.S) India Maharashtra, India
Corresponding author email: priyamhaske9561@gmail.com , pgdamle8@gmail.com

Abstract: The increasing demand for sustainable renewable energy and limited land availability have accelerated the development of Floating Photovoltaic (FPV) systems as an efficient alternative to conventional solar installations. FPV technology provides advantages such as improved land utilization, reduced water evaporation, and enhanced photovoltaic efficiency due to the cooling effect of water. However, existing floating solar structures face major challenges including structural deformation, wind–wave interaction, hydrodynamic instability, mooring failure, UV degradation, and reduced material durability under long-term environmental exposure.

This research proposes an AI-assisted multi-physics framework for the design optimization and structural enhancement of composite floating solar photovoltaic structures using Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), and Fluid–Structure Interaction (FSI) techniques. A 3D floating platform model is developed and optimized considering buoyancy stability, PV module arrangement, and environmental loading conditions. High-Density Polyethylene (HDPE)-based composite material is selected for float development due to its lightweight nature, corrosion resistance, and excellent durability. Reinforcement materials and UV stabilizing additives are incorporated to improve mechanical strength, impact resistance, and ageing performance. Material characterization is performed through tensile, flexural, impact, hardness, and durability testing. The proposed methodology integrates mathematical modelling, FEA-based structural evaluation, CFD-based hydrodynamic analysis, and FSI simulation to investigate stress distribution, deformation behaviour, pressure variation, and wave-induced dynamic response. Machine learning models such as ANN, Random Forest, and XGBoost are utilized for performance prediction and optimization using simulation-generated datasets. Results demonstrate improved structural stability, reduced deformation, enhanced safety factor, optimized hydrodynamic behaviour, and better energy performance compared with conventional floating structures.

The study concludes that the integration of composite materials, multi-physics simulation, and artificial intelligence provides an effective approach for developing reliable, durable, and energy-efficient next-generation floating photovoltaic systems. The proposed framework supports future implementation of intelligent FPV platforms with digital twin monitoring and predictive maintenance capabilities.

Keywords: Floating Photovoltaic System (FPV), Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), Fluid–Structure Interaction (FSI), HDPE Composite Material, Hydrodynamic Stability Analysis, AI-Based Structural Optimization, Machine Learning, Digital Twin Technology, Renewable Energy System.

1. Introduction

1.1 Background of Floating Solar Photovoltaic (FPV) Technology

The rapid growth of renewable energy technologies has accelerated the transformation of conventional land-based photovoltaic (PV) systems toward innovative Floating Photovoltaic (FPV) energy generation platforms. Traditional ground-mounted solar installations require extensive land areas, which creates challenges related to land availability, agricultural competition, and environmental impact [12]. To overcome these limitations, FPV technology has emerged as an advanced alternative where solar modules are mounted on floating structures deployed over reservoirs, lakes, irrigation ponds, and offshore water surfaces [47]. The evolution from land-based PV systems to floating solar technology has introduced several advantages, including improved land utilization, enhanced power generation efficiency due to natural water-cooling effects, and reduction in water evaporation losses [83]. Recent developments in floating renewable energy systems demonstrate that FPV installations can provide higher energy density while maintaining ecological sustainability and efficient utilization of unused water bodies [26].

Floating Photovoltaic systems have gained significant attention due to their ability to address the global demand for clean energy production and sustainable water resource management. The interaction between the solar modules and surrounding water environment provides passive cooling, reducing the operating temperature of photovoltaic cells and improving conversion efficiency [59]. Additionally, partial coverage of water surfaces by floating modules minimizes direct solar radiation exposure, reducing evaporation rates and supporting water conservation strategies in regions facing water scarcity [101]. Compared with conventional solar farms, FPV systems offer improved energy generation capability, reduced land acquisition costs, and better integration with existing hydropower reservoirs [34]. Therefore, floating solar technology is considered a promising solution for achieving renewable energy targets while balancing energy–water–environment relationships [76].

Despite these benefits, the practical implementation of large-scale floating solar systems faces several structural and operational challenges. Floating platforms are continuously exposed to environmental loads such as wind pressure, wave forces, water currents, temperature variations, and long-term material degradation [18]. These external effects influence the structural stability, fatigue resistance, and service life of floating components. The floating structure must maintain adequate buoyancy, mechanical strength, and stability under complex operating conditions [92]. Furthermore, the development of optimized floating platforms requires accurate numerical modeling and advanced computational techniques to evaluate structural performance, deformation behavior, and failure mechanisms before real-world deployment [55].

1.2 Structural and Environmental Challenges in FPV Systems

Floating photovoltaic structures operate in complex aquatic environments where continuous interaction between fluid forces and structural components creates significant design challenges. Unlike conventional ground-mounted PV systems, FPV platforms experience dynamic loads generated by wind–wave interaction, water currents, and fluctuating environmental conditions [7]. Wave-induced motion produces six-degree-of-freedom responses including surge, sway, heave, roll, pitch, and yaw, which directly influence platform stability and solar panel alignment [66]. Excessive structural movement can result in reduced energy output, connection failure, and mechanical fatigue of floating components [41]. Therefore, understanding fluid-induced loading conditions is essential for improving the long-term reliability of floating solar structures.

Hydrostatic and hydrodynamic forces play a major role in determining the performance and safety of FPV systems. Hydrostatic effects mainly include buoyancy force, floating equilibrium, and restoring stability, whereas hydrodynamic effects involve wave pressure distribution, drag forces, and fluid-induced vibrations [89]. Improper consideration of these parameters during the design phase may lead to excessive deformation, stress concentration, and instability of floating platforms [22]. Advanced numerical approaches such as Computational Fluid Dynamics (CFD) and Hydroelastic modeling are increasingly applied to analyze the interaction between floating structures and surrounding water environments [104]. Accurate prediction of these responses helps optimize float geometry, anchoring arrangements, and structural configurations [63].

Another critical challenge in FPV systems is the reliability of mooring and anchoring mechanisms. Mooring systems are responsible for maintaining the position and orientation of floating platforms under varying environmental conditions [38]. Continuous cyclic loading caused by waves and wind can produce fatigue damage, increased mooring tension, and eventual system failure [97]. Optimized mooring designs are necessary to minimize structural displacement and improve operational safety. Additionally, thermal effects significantly influence photovoltaic efficiency because excessive PV module temperature reduces electrical output performance [15]. Although the cooling effect of water improves FPV efficiency compared with land-based systems, thermal variations must be evaluated to achieve stable long-term performance [72].

1.3 Advanced Composite Material Applications in FPV

The selection of suitable materials is one of the most important factors influencing the durability, strength, and performance of floating photovoltaic structures. High-density polyethylene (HDPE) has become a widely preferred material for FPV floating platforms due to its lightweight characteristics, excellent corrosion resistance, high buoyancy performance, and suitability for marine environments [31]. Compared with metallic structures, HDPE-based polymer composites provide improved resistance against moisture absorption, chemical exposure, and environmental degradation [68]. The integration of reinforcement materials into HDPE matrices has further improved mechanical properties such as tensile strength, impact resistance, stiffness, and dimensional stability [93].

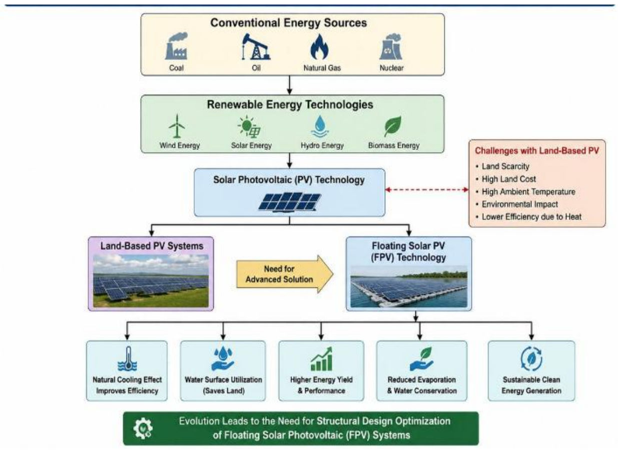


Figure1.1: Evolution of Floating Solar Photovoltaic technology

Advanced polymer composite materials are being investigated to enhance the lifetime and structural reliability of floating solar platforms. The addition of fillers, UV stabilizers, carbon-based materials, and hybrid reinforcements improves resistance against ultraviolet radiation, thermal ageing, and mechanical failure [45]. Since FPV systems are continuously exposed to sunlight, temperature variations, and water environments, UV degradation is one of the major concerns affecting polymer performance [108]. Long-term exposure causes molecular chain breakdown, surface cracking, reduction in mechanical strength, and loss of material properties [24]. Therefore, material optimization through composite modification is essential for achieving improved durability and extended service life of FPV components.

Mechanical strength and durability requirements for floating structures are significantly different from conventional PV mounting systems. Floating modules must withstand static loads from solar panels, dynamic loads from water movement, and environmental stresses throughout their operating lifetime [81]. Experimental characterization methods such as tensile testing, flexural analysis, hardness measurement, impact testing, and ageing studies are commonly performed to evaluate composite performance [57]. Combining experimental material evaluation with numerical simulation provides a reliable approach for designing high-performance composite floating solar structures [99].

1.4 Role of Computational Simulation Techniques

Computational simulation methods have become essential tools for analyzing, optimizing, and validating floating photovoltaic structures before physical implementation. Finite Element Analysis (FEA) is widely used for predicting mechanical behavior, stress distribution, deformation patterns, and structural failure conditions under different loading environments [11]. Through FEA-based numerical modeling, engineers can optimize floating platform geometry, reduce material usage, and improve structural reliability [74]. Parameters such as equivalent stress, strain distribution, displacement response, fatigue life, and factor of safety can be evaluated effectively using advanced finite element techniques [50].

Computational Fluid Dynamics (CFD) provides an advanced approach for analyzing water–air interaction and hydrodynamic behavior around floating solar structures. CFD simulations allow the prediction of pressure distribution, velocity fields, turbulence effects, and wave-induced forces acting on floating platforms [87]. Multiphase CFD models are especially useful for understanding complex interaction between air, water, and floating bodies under realistic environmental conditions [29]. These simulations help improve float design, minimize drag forces, and enhance stability against external disturbances [106].

Fluid–Structure Interaction (FSI) combines structural and fluid simulations to provide a more realistic representation of FPV performance. In FSI-based analysis, hydrodynamic forces calculated from CFD models are transferred to structural models to evaluate deformation and stress response [54]. Two-way coupled FSI approaches provide higher accuracy by considering simultaneous interaction between fluid flow and structural movement [100]. The integration of FEA, CFD, and FSI creates a multi-physics framework capable of predicting Hydroelastic behavior, fatigue performance, and long-term structural stability of floating solar systems [69].

2. Literature Review and Technological Background

2.1 Review of Existing Floating Solar PV Technologies

Floating Photovoltaic (FPV) technology has rapidly developed as an innovative renewable energy solution by utilizing unused water surfaces such as reservoirs, lakes, irrigation ponds, and offshore regions for solar energy generation. Conventional land-based photovoltaic systems have limitations related to land availability, environmental disturbance, and installation constraints, which have accelerated the development of floating solar platforms [14]. Modern FPV systems consist of photovoltaic modules, floating support structures, anchoring systems, electrical components, and monitoring technologies designed to operate under complex aquatic environmental conditions [52]. Various floating technologies have been introduced to improve structural reliability, energy efficiency, and long-term operational stability [87].

Pontoon-based FPV systems are among the most widely adopted floating structures due to their simple design, high buoyancy capacity, and ease of installation. These systems generally consist of interconnected floating pontoons manufactured from polymer materials such as high-density polyethylene (HDPE), which provide corrosion resistance and lightweight characteristics [33]. Pontoon structures maintain solar panel stability by distributing loads uniformly across the floating platform while resisting hydrostatic pressure and wave-induced forces [96]. However, large-scale pontoon-based systems experience challenges related to dynamic motion, connection failures, and structural deformation caused by continuous environmental loading [61].

Modular floating structures have been developed to overcome the limitations of traditional pontoon systems by introducing flexible arrangements and scalable configurations. These systems consist of multiple floating units connected through mechanical joints, allowing improved adaptability to water-level variations and wave movements [108]. Modular FPV designs provide advantages such as simplified transportation, easier maintenance, and improved structural redundancy [42]. The performance of these floating arrays strongly depends on module arrangement, connection stiffness, and hydrodynamic response under operating conditions [79].

Flexible and semi-flexible floating platforms represent the latest advancements in FPV technology, particularly for large-scale and offshore applications. Unlike rigid floating structures, flexible platforms allow controlled deformation under wave loading, reducing stress concentration and improving fatigue resistance [25]. Semi-flexible designs combine structural stiffness and flexibility to achieve improved hydro-elastic behavior, reducing the risk of component failure under extreme environmental conditions [103]. However, further research is required to optimize material selection, structural configuration, and long-term durability of these advanced floating systems [68].

2.2 Review of Structural Analysis Methods

Structural analysis plays a critical role in the design and performance evaluation of floating photovoltaic systems because these structures operate continuously under mechanical and environmental loading conditions. Traditional static structural analysis methods are widely applied to evaluate stress distribution, displacement behavior, and load-bearing capacity of FPV components [9]. Static analysis considers the effects of solar panel weight, floating structure self-weight, buoyancy forces, and external pressure conditions to determine structural safety [74]. These methods provide fundamental information regarding maximum deformation, equivalent stress, and factor of safety during the initial design stage [38].

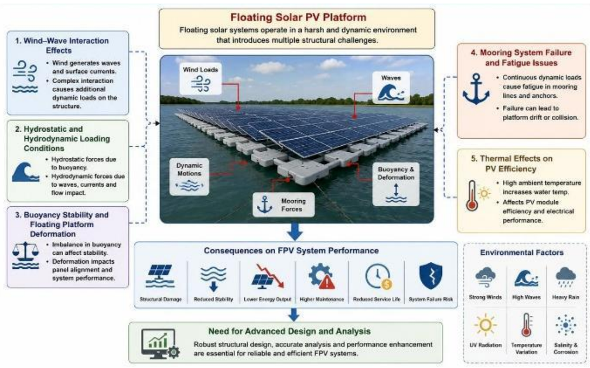


Figure1.2: Structural Challenges in Floating Solar Platform

Although static analysis provides essential structural information, floating platforms are continuously exposed to dynamic environmental conditions including wind, waves, and water currents. Therefore, dynamic response prediction methods are required to accurately evaluate real-time structural behavior [81]. Dynamic analysis investigates time-dependent responses such as vibration characteristics, displacement variations, natural frequency, and resonance effects under fluctuating loads [57]. Advanced dynamic simulation approaches enable the prediction of structural motion and help improve the reliability of floating solar platforms in harsh environmental conditions [99].

Fatigue and failure analysis have become important research areas for ensuring the long-term durability of FPV systems. Repeated cyclic loading generated by waves and wind can initiate cracks, material degradation, and structural failure over extended operating periods [46]. Fatigue analysis techniques evaluate stress cycles, damage accumulation, and expected service life of floating components [91]. Modern approaches combine experimental testing with computational simulation methods to identify critical failure regions and optimize structural designs for enhanced durability [110].

2.3 Review of Numerical Simulation Techniques

Numerical simulation techniques provide an effective approach for analyzing complex structural and fluid interactions in floating photovoltaic systems. Finite Element Method (FEM)-based analysis is extensively used to investigate deformation behavior, mechanical strength, and failure mechanisms of floating structures [18]. FEM divides complex geometries into smaller elements, allowing accurate prediction of stress concentration, strain distribution, and displacement response under different loading conditions [65]. Advanced FEM techniques support material optimization and structural modifications before physical prototype development [102].

Computational Fluid Dynamics (CFD)-based hydrodynamic modeling has become an essential tool for evaluating the interaction between floating platforms and surrounding water environments. CFD analysis solves fluid flow equations to predict pressure distribution, velocity variation, turbulence characteristics, and wave effects acting on floating structures [27]. Multiphase CFD models are commonly used for FPV applications because they accurately represent air–water interfaces and wave propagation effects [86]. These simulations help researchers optimize float geometry, minimize hydrodynamic resistance, and improve overall floating stability [49].

Fluid–Structure Interaction (FSI) simulation combines structural and fluid analysis to evaluate the coupled response between floating platforms and surrounding water bodies. One-way FSI methods transfer hydrodynamic loads obtained from CFD analysis into structural models to calculate deformation and stress response [71]. However, one-way coupling does not consider the influence of structural movement on fluid behavior, which limits prediction accuracy under highly dynamic conditions [35]. Two-way FSI approaches overcome this limitation by allowing continuous exchange of information between fluid and structural domains, resulting in more realistic prediction of hydro-elastic performance [106].

2.4 Hydrodynamic Behaviour of Floating Platforms

The hydrodynamic behavior of floating photovoltaic platforms is a key factor affecting their stability, safety, and operational efficiency. Floating structures continuously interact with water waves, currents, and wind-induced forces, producing complex dynamic responses [23]. Wave-induced motion can significantly influence structural integrity, electrical performance, and alignment of photovoltaic modules [88]. Therefore, accurate prediction of hydrodynamic response is necessary for developing reliable floating solar systems suitable for different environmental conditions [56].

Floating platforms experience six-degree-of-freedom motion responses including surge, sway, heave, roll, pitch, and yaw due to external hydrodynamic excitation [12]. Surge and sway represent horizontal movements caused by wave and current forces, while heave represents vertical displacement due to changing water surface elevation [94]. Rotational movements such as roll, pitch, and yaw affect solar panel orientation and may reduce power generation efficiency [40]. Excessive platform motion can also increase stress on connections, mooring lines, and electrical systems, leading to premature failure [78].

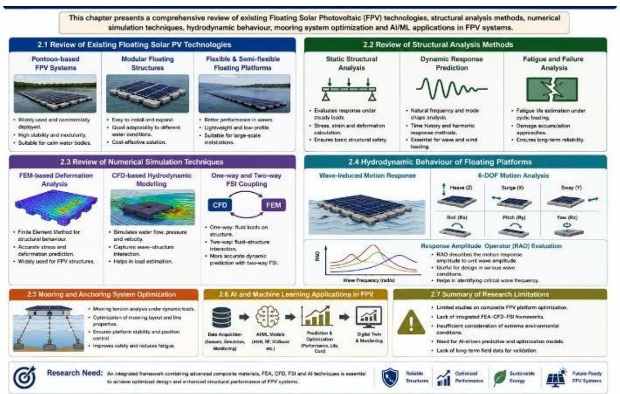


Figure1.3: Technological Background of Review

Response Amplitude Operator (RAO) analysis is widely used to evaluate the dynamic behavior of floating structures under wave excitation. RAO represents the relationship between input wave characteristics and resulting platform motion responses [63]. This method provides important information regarding resonance conditions, stability limits, and operational performance of floating structures [105]. Hydrodynamic analysis using RAO evaluation supports the optimization of floating structure geometry, mooring arrangement, and overall system reliability [31].

2.5 Mooring and Anchoring System Optimization

Mooring and anchoring systems are essential components responsible for maintaining the position and stability of floating photovoltaic platforms. Unlike fixed solar structures, FPV systems require flexible but reliable anchoring arrangements to withstand environmental forces while allowing controlled movement [19]. Mooring systems must resist wind loads, wave forces, water currents, and water-level variations throughout the operational lifetime of the system [84]. Improper mooring design can result in excessive displacement, structural instability, and component failure [55].

Mooring tension analysis is performed to evaluate load distribution and safety performance of anchoring systems under different environmental conditions. Dynamic tension variations occur due to continuous movement of floating platforms caused by wave and wind excitation [97]. Numerical models are commonly used to predict maximum tension, fatigue damage, and failure probability of mooring components [37]. Optimization techniques are applied to determine suitable mooring length, material properties, anchor locations, and connection arrangements [109].

Advanced floating stability control mechanisms focus on reducing unwanted platform motion while improving operational reliability. Hydrodynamic optimization, damping systems, and adaptive mooring configurations have been investigated to enhance stability performance [70]. Dynamic positioning behavior analysis helps determine the movement characteristics of floating platforms under changing environmental loads [45]. Effective mooring optimization improves safety, reduces maintenance requirements, and extends the lifetime of FPV systems [100].

2.6 AI and Machine Learning Applications in FPV

Artificial Intelligence (AI) and Machine Learning (ML) technologies have introduced new opportunities for intelligent monitoring, prediction, and optimization of floating photovoltaic systems. Conventional simulation approaches require significant computational time for analyzing complex fluid–structure interactions, whereas AI-based models can provide faster prediction with high accuracy [11]. Machine learning algorithms are increasingly applied for structural health monitoring, energy forecasting, fault detection, and performance optimization of renewable energy systems [75].

Digital twin-based monitoring represents an advanced approach for real-time evaluation of FPV system performance. A digital twin creates a virtual representation of the physical floating solar system by integrating sensor data, numerical simulation results, and machine learning models [98]. This technology enables continuous monitoring of structural deformation, mooring forces, environmental conditions, and energy output variations [44]. Predictive maintenance strategies using digital twins can reduce failure risks and improve operational efficiency [107].

Machine learning models such as Artificial Neural Networks (ANN), Random Forest (RF), and Extreme Gradient Boosting (XGBoost) have demonstrated strong capability for predicting complex nonlinear behavior in floating structures [29]. These algorithms can estimate displacement response, mooring tension, power output, and structural performance based on simulation or experimental datasets [90]. Integration of AI techniques with FEA, CFD, and FSI models enables intelligent optimization frameworks for designing next-generation floating photovoltaic platforms [64].

2.7 Summary of Research Limitations

Although significant progress has been achieved in floating photovoltaic technology, several limitations remain in existing research related to structural design, computational modeling, and intelligent optimization. Most available studies focus mainly on energy performance and installation feasibility, while detailed analysis of structural durability under combined environmental loading conditions remains insufficient [21]. The interaction between wave dynamics, structural deformation, and material degradation requires further investigation for reliable large-scale FPV deployment [82].

Existing numerical studies often analyze structural and fluid behavior separately, which reduces accuracy in predicting real operating conditions. Limited research has integrated FEM, CFD, and two-way Fluid–Structure

Interaction approaches for comprehensive hydro-elastic evaluation of floating solar platforms [53]. Additionally, the long-term performance of HDPE-based composite materials under UV exposure, fatigue loading, and environmental ageing conditions requires further experimental validation [95].

Current optimization techniques also lack integration between advanced computational simulations and artificial intelligence-based prediction systems. The development of AI-assisted multi-physics frameworks combining FEA, CFD, FSI, and machine learning can significantly improve design efficiency, reduce computational cost, and enhance structural reliability [110]. Therefore, future research must focus on intelligent, sustainable, and optimized floating solar photovoltaic structures capable of operating efficiently under complex environmental conditions [69].

3. Proposed Methodology and System Development

3.1 Proposed Floating Solar Structure Design Framework

The proposed methodology focuses on the development of an advanced Floating Photovoltaic (FPV) structural framework by integrating material optimization, computational simulation, and artificial intelligence-based prediction techniques. The main objective of the proposed design framework is to enhance the mechanical stability, hydrodynamic performance, and energy efficiency of floating solar platforms under real environmental conditions [18]. The floating solar structure consists of photovoltaic modules, composite floating units, interconnection mechanisms, mooring arrangements, and supporting components designed to withstand static and dynamic loading conditions [76]. Unlike conventional floating structures, the proposed system considers the combined effects of structural loading, water interaction, wind pressure, wave excitation, and long-term environmental degradation during the design stage [42].

A multi-physics simulation approach is implemented by integrating Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), and Fluid–Structure Interaction (FSI) techniques to accurately predict the behavior of floating photovoltaic systems [91]. The complete framework involves geometrical modeling, material characterization, structural analysis, hydrodynamic simulation, coupled response evaluation, and machine learning-based optimization [57]. Simulation results obtained from computational models are further utilized for developing AI-based predictive algorithms to identify optimized design parameters and improve structural reliability [103]. This integrated approach provides a systematic pathway for designing next-generation intelligent FPV systems with improved durability, reduced maintenance requirements, and enhanced renewable energy performance [29].

3.2 Geometrical Modelling of Floating PV Platform

The geometrical modeling of the floating photovoltaic platform is an essential stage for analyzing structural behavior and optimizing the overall performance of the system. A three-dimensional CAD model of the floating structure is developed using advanced design software by considering geometric parameters such as float dimensions, wall thickness, module arrangement, connection points, and load distribution characteristics [64]. The CAD model represents the actual physical configuration of the FPV system and acts as the primary input for numerical simulations including FEA and CFD analysis [22]. Accurate geometric representation helps in predicting stress concentration regions, deformation patterns, and hydrodynamic responses under different environmental loading scenarios [95].

Float geometry optimization is performed to improve buoyancy performance, structural strength, and stability of the floating platform. Various design parameters such as float shape, volume distribution, surface profile, and structural reinforcement arrangement are optimized to achieve maximum load-carrying capacity with minimum material consumption [36]. The optimized floating geometry reduces drag forces, improves wave resistance, and enhances overall platform stability during operation [81].

Design modifications are evaluated through iterative simulation processes to achieve improved structural performance and operational safety [108].

PV module arrangement design plays an important role in maintaining structural balance and maximizing solar energy generation efficiency. The positioning and orientation of solar modules influence load distribution, center of gravity, wind resistance, and maintenance accessibility [53]. Proper arrangement ensures uniform stress transfer across the floating platform while reducing localized deformation and connection failures [88]. Optimized module configuration improves system reliability and supports large-scale deployment of floating solar photovoltaic plants [14].

3.3 Material Selection and Composite Development

Material selection is one of the most critical aspects in the development of durable floating photovoltaic structures because the floating components continuously operate under water exposure, solar radiation, temperature variation, and mechanical loading conditions [25]. High-Density Polyethylene (HDPE) is selected as the primary polymer matrix material due to its excellent buoyancy characteristics, lightweight nature, corrosion resistance, chemical stability, and suitability for marine applications [74]. Compared with metallic floating structures, HDPE provides improved resistance against rust formation, moisture absorption, and environmental degradation [39].

To enhance the mechanical and environmental performance of HDPE floating structures, composite material development is performed using suitable filler and reinforcement materials. The incorporation of additives such as calcium carbonate, carbon black, glass fiber, nano-fillers, and UV stabilizers improves stiffness, tensile strength, impact resistance, and weathering performance [97]. Filler material reinforcement optimization is conducted by varying composition percentages and evaluating their influence on mechanical and thermal properties [61]. The optimized composite formulation provides improved structural strength while maintaining required flexibility and floating capability [105].

Mechanical property characterization is performed to validate the suitability of developed composite materials for FPV applications. Experimental tests including tensile strength, flexural strength, impact resistance, hardness measurement, density analysis, melt flow rate evaluation, and ageing tests are conducted according to standard testing procedures [44]. These experimentally obtained material properties are integrated into numerical simulation models for accurate prediction of structural behavior [86]. The combination of experimental characterization and computational analysis improves material selection accuracy and ensures long-term structural durability [110].

3.4 Mathematical Modelling of Floating Structure

Mathematical modeling provides the theoretical foundation required to understand the mechanical, hydrostatic, and dynamic behavior of floating photovoltaic systems. The floating structure operates based on the equilibrium between gravitational forces, buoyancy forces, environmental loads, and structural resistance [17]. Analytical models are developed to evaluate floating stability, displacement characteristics, stress response, and loading effects before performing numerical simulations [72]. These mathematical formulations help optimize structural dimensions and validate computational results [48].

3.4.1 Buoyancy Force Analysis

Buoyancy force analysis is performed based on Archimedes' principle to determine the floating capacity and stability of the FPV structure. The upward buoyancy force generated by displaced water must be greater than or equal to the total weight of the solar panels, supporting frame, floating structure, and additional components [34]. Accurate estimation of buoyancy force ensures that the platform maintains sufficient freeboard and prevents excessive sinking during operation [89]. The buoyancy analysis also helps optimize float volume and material utilization while maintaining safe operating conditions [55].

3.4.2 Hydrostatic Stability Calculation

Hydrostatic stability analysis evaluates the ability of the floating structure to return to its original position after disturbance caused by external forces. Stability parameters such as center of gravity, center of buoyancy, metacentric height, and restoring moment are considered during the design process [67]. A stable floating platform requires appropriate balance between structural weight distribution and buoyancy forces [93]. Hydrostatic evaluation minimizes the risk of overturning, excessive tilting, and unstable motion during environmental variations [27].

3.4.3 Wind and Wave Loading Model

Wind and wave loading models are developed to represent realistic environmental conditions acting on floating photovoltaic platforms. Wind forces generate aerodynamic pressure on solar panels, while wave forces create hydrodynamic loading on floating structures [79]. These combined loads produce structural displacement, vibration, and fatigue effects over long-term operation [41]. Mathematical representation of environmental loading improves the accuracy of numerical simulations and supports the development of reliable FPV designs [102].

3.4.4 Structural Stress-Strain Relationship

The stress-strain relationship defines the mechanical response of floating materials under applied loading conditions. Material behavior is analyzed by considering elastic deformation, stiffness characteristics, strength limitations, and failure criteria [13]. Understanding stress-strain behavior is essential for predicting deformation, fatigue damage, and structural safety under static and dynamic loading conditions [69]. These properties are implemented in finite element models to obtain realistic simulation results [98].

The mathematical modelling of the floating solar photovoltaic structure is developed by considering buoyancy force, hydrostatic stability, environmental loading, structural deformation, hydrodynamic interaction, and energy performance. The floating platform is assumed to be subjected to self-weight, PV panel load, wind pressure, wave excitation, and fluid forces. The governing mathematical equations are formulated as follows:

1. Buoyancy Force Analysis

The floating PV platform follows **Archimedes' principle**, where the upward buoyant force generated by displaced water balances the total structural weight.

$$F_B = \rho_w \times g \times V_d$$

Were,

F_B= Buoyancy force (N)

ρ_w= Density of water (kg/m³)

g= Gravitational acceleration (9.81 m/s²)

V_d= Volume of displaced water (m³)

The total gravitational load acting on the floating system is:

$$W_T = (m_f + m_p + m_s)g$$

Were,

W_T= Total weight of FPV system (N)

m_f= Mass of floating structure (kg)

m_p= Mass of PV modules (kg)

m_s= Mass of supporting structure (kg)

For stable floating condition:

$$F_B \geq W_T$$

The safety factor against sinking is:

$$SF_b = \frac{F_B}{W_T}$$

2. Floating Depth Calculation

The submerged depth of the floating structure is calculated as:

$$h_s = \frac{V_d}{A_f}$$

Were,

h_s= Submerged height of float (m)

A_f= Floating surface area (m²)

Freeboard height:

$$h_f = H - h_s$$

Were,

H= Total float height (m)

h_f= Height above water surface

3. Hydrostatic Stability Analysis

The stability of the floating solar platform depends on the relationship between center of gravity and center of buoyancy.

Metacentric height:

$$GM = KB + BM - KG$$

Were,

GM= Metacentric height

KB= Center of buoyancy location

KG= Center of gravity location

Metacentric radius:

$$BM = \frac{I}{V_d}$$

Were,

I= Moment of inertia of water plane area

V_d= Displaced volume

Stable floating condition:

$$GM > 0$$

4. Wind Loading Model

Wind pressure acting on PV panels is calculated using:

$$P_w = \frac{1}{2}\rho_a C_d V_w^2$$

Were,

P_w= Wind pressure (N/m²)

ρ_a= Air density (kg/m³)

C_d= Drag coefficient

V_w= Wind velocity (m/s)

Total wind force:

$$F_w = P_w A_p$$

Were,

A_p= Projected PV panel area

5. Wave Force Calculation (Morison Equation)

Hydrodynamic wave loading on the floating structure is estimated by:

$$F_{wave} = F_D + F_I$$

Drag force:

$$F_D = \frac{1}{2}\rho_w C_D A V^2$$

Inertia force:

$$F_I = \rho_w C_M V_0 a$$

Were,

C_D= Drag coefficient

C_M= Inertia coefficient

V= Water particle velocity

a= Water acceleration

V_0= Submerged volume

6. Structural Stress–Strain Modelling

For HDPE composite floating structure:

Stress:

$$\sigma = \frac{F}{A}$$

Were,

σ= Stress (MPa)

F = Applied force

A = Cross-sectional area

Strain:

$$\epsilon = \frac{\Delta L}{L}$$

Were,

ϵ= Strain

ΔL= Change in length

L = Original length

Elastic modulus:

$$E = \frac{\sigma}{\epsilon}$$

7. Finite Element Analysis (FEA) Governing Equation

The structural behaviour is represented using:

$$[K]\{u\} = \{F\}$$

Were,

[K] = Global stiffness matrix

{u} = Displacement vector

{F} = Applied force vector

Dynamic structural response:

$$[M]\ddot{x} + [C]\dot{x} + [K]x = F(t)$$

Were,

[M] = Mass matrix

[C] = Damping matrix

[K] = Stiffness matrix

8. Von-Mises Stress Calculation

The failure behaviour of composite floating structures is evaluated by:

$$\sigma_v = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}$$

Safe design condition:

$$\sigma_v < \sigma_y$$

Were,

σ_y= Yield strength of material

9. CFD Governing Equations

Continuity Equation

$$\nabla . V = 0$$

Navier–Stokes Momentum Equation

$$\rho(V. \nabla V) = -\nabla P + \mu \nabla^2 V + \rho g$$

Were,

P = Pressure

μ = Dynamic viscosity

V = Fluid velocity

10. Fluid–Structure Interaction (FSI) Coupling

Fluid force transferred to structural model:

$$F_{FSI} = \int_A \quad P\, dA$$

Structural deformation feedback:

$$X_s = f(F_{fluid}, K)$$

Coupled condition:

$$d_f = d_s \sigma_f . n = \sigma_s . n$$

Were,

d_f, d_s= Fluid and structure displacement

σ_f, σ_s= Fluid and structural stress

11. PV Energy Efficiency Model

Solar power output:

$$P = \eta A_s G$$

Were,

P = Generated power

η = PV efficiency

A_s= Solar panel area

G = Solar irradiation

Temperature corrected efficiency:

$$\eta_T = \eta_{ref}[1 - \beta(T - T_{ref})]$$

Were,

β = Temperature coefficient

T = PV operating temperature

3.5 Finite Element Analysis (FEA) Methodology

Finite Element Analysis is implemented to evaluate the structural performance of the floating photovoltaic platform under different mechanical and environmental loading conditions. The developed CAD model is converted into a finite element model by generating an optimized computational mesh consisting of smaller elements and nodes [21]. Mesh generation and convergence analysis are performed to achieve accurate numerical results while maintaining computational efficiency [62]. Proper mesh refinement is applied in critical regions where high stress concentration and deformation are expected [87].

Boundary conditions are applied according to actual operating conditions, including solar panel loading, buoyancy support, wind pressure, and hydrodynamic forces [45]. Equivalent stress analysis using Von-Mises criteria is conducted to identify maximum stress regions and possible failure locations within the structure [94]. Total deformation analysis evaluates displacement patterns and structural stiffness under applied loads [32]. The obtained results provide important information for improving geometry, material distribution, and design safety [77].

Fatigue life prediction is performed to estimate the long-term reliability of floating structures subjected to repeated cyclic loading. Environmental forces such as waves and wind create continuous stress variations that may cause progressive damage accumulation [59]. Fatigue analysis predicts service life, damage locations, and maintenance requirements of floating components [109]. This approach improves durability and reduces unexpected structural failures during long-term operation [84].

3.6 Computational Fluid Dynamics (CFD) Modelling

Computational Fluid Dynamics modeling is performed to analyze the interaction between floating structures and surrounding water-air environments. A computational fluid domain is created around the FPV structure to simulate realistic hydrodynamic conditions [16]. The fluid domain represents water depth, wave conditions, air flow regions, and boundary interactions required for accurate simulation [73]. CFD analysis helps predict pressure variation, velocity distribution, drag forces, and turbulence effects acting on floating platforms [51].

Multiphase water-air modeling techniques are used to represent the interface between water and atmospheric conditions. The Volume of Fluid (VOF) approach is commonly applied to capture wave formation, free surface movement, and interaction with floating bodies [99]. Turbulence modeling is implemented to analyze complex fluid flow behavior generated by waves, currents, and wind forces [38]. These models improve understanding of hydrodynamic performance and support optimization of floating structure designs [104].

Pressure distribution analysis provides detailed information about external forces acting on floating components. Hydrodynamic pressure variations influence deformation, stability, and fatigue characteristics of

FPV structures [26]. The obtained CFD results are further transferred into structural simulation models for coupled fluid–structure analysis [90].

3.7 Fluid–Structure Interaction (FSI) Simulation

Fluid–Structure Interaction simulation provides a comprehensive approach for evaluating the coupled behavior between floating solar structures and surrounding fluid environments. In the proposed methodology, pressure loads obtained from CFD simulations are transferred into FEM models to analyze structural deformation and stress response [35]. This coupling method provides a realistic representation of operating conditions compared with independent fluid or structural analysis [82].

Coupled hydro-elastic simulation evaluates the simultaneous interaction between hydrodynamic forces and structural flexibility. Floating platforms deform due to wave loading, and this deformation influences surrounding fluid behavior, creating a continuous interaction process [66]. Two-way FSI simulation improves prediction accuracy by considering feedback between structural displacement and fluid pressure variation [101].

Dynamic deformation prediction helps evaluate real-time response characteristics of floating photovoltaic systems. Parameters such as displacement amplitude, vibration response, stress fluctuation, and fatigue behavior are analyzed under different environmental scenarios [56]. FSI-based evaluation supports the development of structurally reliable and environmentally adaptive floating solar platforms [107].

4. Material Study

4.1 Material Study of Polypropylene (PP)

Polypropylene (PP) is a semi-crystalline thermoplastic polymer widely used in engineering and renewable energy applications due to its low density, excellent chemical resistance, and good thermal stability.

PP exhibits superior fatigue resistance and moderate mechanical strength, making it suitable for lightweight structural components. It has a density ranging from 895–920 kg/m³, a melting temperature of approximately 160–170°C, and very low water absorption (0.01–0.03%). However, PP exhibits lower UV resistance compared to HDPE and therefore requires UV stabilizers for long-term outdoor applications such as floating photovoltaic (FPV) systems.

Figure1.4: Polypropylene (PP)

4.2 Material Study High-Density Polyethylene (HDPE)

High-Density Polyethylene (HDPE) is a thermoplastic polymer known for its high strength-to-density ratio, excellent chemical inertness, and superior environmental durability.

HDPE possesses a density ranging from 930–970 kg/m³, high impact resistance, and excellent resistance to moisture absorption (<0.01%).

Figure1.5: High-Density Polyethylene (HDPE-MA180)

The material exhibits good UV stability when compounded with carbon black and UV stabilizers, making it highly suitable for outdoor applications. Owing to its lightweight nature, corrosion resistance, and excellent buoyancy characteristics, HDPE is considered one of the most promising materials for floating solar structures used in farm ponds and reservoirs.

Table1.1: Specifications of PP and HDPE with Important Processing Parameters

Property	PP (Polypropylene)	HDPE (High Density Polyethylene)
Material Type	Semi-crystalline Thermoplastic	Semi-crystalline Thermoplastic
Density (kg/m³)	895 – 920	930 – 970
Tensile Strength (MPa)	30 – 40	20 – 37
Flexural Modulus (GPa)	1.2 – 1.8	0.8 – 1.5
Elongation at Break (%)	100 – 600	100 – 1000
Impact Resistance	Good	Excellent
Water Absorption (%)	0.01 – 0.03	< 0.01
Melting Temperature (°C)	160 – 170	130 – 137
Maximum Service Temperature (°C)	100 – 110	80 – 120
Chemical Resistance	Excellent	Excellent
UV Resistance	Moderate (requires stabilizer)	Excellent (with carbon black/UV stabilizer)
Corrosion Resistance	Excellent	Excellent
Buoyancy	Good	Excellent
Recyclability	Recyclable	Recyclable
Typical Applications	Automotive parts, containers, pipes	Floating docks, FPV floats, tanks, pipes
★ Injection Molding Temperature	220 – 280 (°C)	180 – 260 (°C)
★ Extrusion Temperature (°C)	190 – 250	180 – 230

★ Mold Temperature (°C)	20 – 80	20 – 70
★ Processing Pressure (MPa)	70 – 140	50 – 100
★ Cooling Time (s)	15 – 40	20 – 60

4.3 Calcium Carbonate ($CaCO_3$)

Calcium Carbonate ($CaCO_3$) is incorporated as an inorganic filler material to improve the stiffness, dimensional stability, and cost-effectiveness of the composite HDPE material.

In the present study, the $CaCO_3$ content is varied from 3% to 6% to investigate its influence on the mechanical properties such as tensile strength, flexural strength, hardness, and density, as well as physical characteristics including shrinkage and thermal stability of the floating structure.

Figure1.6: Calcium Carbonate ($CaCO_3$)

4.4 Zinc Oxide (ZnO)

Zinc Oxide (ZnO) is added to the composite as a multifunctional additive due to its excellent ultraviolet (UV) absorption capability and antimicrobial properties.

The ZnO concentration is varied from 0.5% to 2.5% to enhance resistance against UV-induced degradation and microbial growth in farm pond environments, thereby improving the long-term durability and performance of the floating photovoltaic structure.

Figure1.7: Zinc Oxide (ZnO)

4.5 UV Stabilizer

Figure1.8: UV Stabilizer

UV Stabilizers are incorporated to protect the polymer matrix from photo-oxidative degradation caused by prolonged exposure to solar radiation.

The concentration of UV stabilizer is varied from 0.5% to 2.5% to improve outdoor weathering resistance, minimize surface cracking, retain mechanical properties, and extend the service life of the floating HDPE composite to more than 10–15 years.

4.6 Carbon Black

Carbon Black is used as an effective UV shielding agent in HDPE composites due to its ability to absorb and dissipate ultraviolet radiation.

The concentration of Carbon Black is varied from 0.5% to 2.5% to enhance UV resistance, improve thermal stability, and increase resistance to environmental aging, thereby ensuring the long-term structural integrity and durability of the floating PV system.

Figure1.9: Carbon Black

5. Material Composition

Table 1.1 presents the composition of composite HDPE specimens developed for Floating Photovoltaic (FPV) structures used in farm pond applications. The base material, High Density Polyethylene (HDPE), is reinforced with varying proportions of Calcium Carbonate ($CaCO_3$) to improve stiffness and dimensional stability, Zinc Oxide (ZnO) to enhance thermal and antimicrobial properties, UV Stabilizer to protect the material from ultraviolet degradation, and Carbon Black to provide UV shielding and improve weather resistance. The optimized combination of these additives aims to enhance the mechanical strength, durability, buoyancy, and long-term environmental resistance of the floating structure under outdoor operating conditions.

Table1.2: Composition of Composite HDPE Specimens with $CaCO_3$, Zinc Oxide, UV Stabilizer, and Carbon Black for Floating PV Structure Development

Specimen	**HDPE**	**$CaCO_3$**	**Zinc Oxide**	**UV Stabilizer**	**Carbon Black**
Specimen 1	500 gms	15 gms (3%)	0.5% (2.5 gms)	0.5% (2.5 gms)	0.5% (2.5 gms)
Specimen 2	500 gms	20 gms (4%)	1% (5 gms)	1% (5 gms)	1% (5 gms)
Specimen 3	500 gms	25 gms (5%)	1.5% (7.5 gms)	1.5% (7.5 gms)	1.5% (7.5 gms)
Specimen 4	500 gms	25 gms (5%)	2% (10 gms)	2% (10 gms)	2% (10 gms)
Specimen 5	500 gms	30 gms (6%)	2.5% (12.5 gms)	2.5% (12.5 gms)	2.5% (12.5 gms)

- HDPE content is maintained constant at 500 g for all specimens.
- The $CaCO_3$ filler content is varied from 3% to 6% to study its effect on mechanical and physical properties.
- Zinc Oxide is added as a UV absorber and antimicrobial additive in the range of 0.5–2.5%.
- UV Stabilizer concentration is varied from 0.5–2.5% to improve outdoor weathering resistance.
- Carbon Black is incorporated as a UV shielding agent to enhance long-term durability and resistance to environmental degradation.

5.1 Material Properties Testing to be Performed

Table1.3: List of properties evaluated for composite HDPE materials and their corresponding ASTM standard test methods

Sr. No.	**Properties**	**Test Methods**
1	Tensile Strength	ASTM D 638
2	Elongation at Break	ASTM D 638
3	Flexural Strength	ASTM D 790
4	Flexural Modulus	ASTM D 790
5	Izod Impact (Notched)	ASTM D 256
6	Shore-D Hardness	ASTM D 2240
7	Density	ASTM D 792
8	MFR (Melt Flow Rate)	ASTM D 1238

The mechanical and physical properties of the composite HDPE/PP materials were evaluated using standardized ASTM test methods to ensure reliable and reproducible results.

Tensile strength and elongation at break were measured according to ASTM D638, while flexural properties were determined using ASTM D790. Impact resistance, hardness, density, and melt flow rate (MFR) were characterized using ASTM D256, ASTM D2240, ASTM D792, and ASTM D1238, respectively. These tests provide comprehensive information regarding the suitability of the developed composite materials for floating photovoltaic (FPV) applications.

5. Procedure of Work

Standard Operating Procedure (SOP)

Mixing of HDPE MA180 with Calcium Carbonate, Zinc Oxide, UV Stabilizer, and Carbon Black in a Roller Mixer

1. Purpose

To establish a standardized procedure for the uniform mixing of HDPE MA180 resin with calcium carbonate, zinc oxide, UV stabilizer, and carbon black using a roller mixer to achieve consistent product quality and dispersion.

2. Scope

This procedure applies to all production personnel involved in the preparation of HDPE compound batches using a roller mixer.

3. Raw Materials

Table1.4: Raw Material

Sr. No.	**Material**	**Function**
1	HDPE MA180	Base polymer resin
2	Calcium Carbonate ($CaCO_3$)	Filler and cost reducer
3	Zinc Oxide (ZnO)	Processing aid and stabilizer
4	UV Stabilizer	Protection against UV degradation
5	Carbon Black	UV protection and black coloration

4. Equipment Required

- Roller Mixer
- Electronic Weighing Scale
- Material Storage Bins/Containers
- Measuring Scoops
- Personal Protective Equipment (PPE)
    - Safety Gloves
    - Safety Goggles
    - Dust Mask/Respirator
    - Safety Shoes

5. Safety Precautions

1. Wear all required PPE before handling materials.
2. Avoid inhalation of calcium carbonate, zinc oxide, UV stabilizer, and carbon black dust.
3. Ensure adequate ventilation around the mixing area.
4. Verify that the roller mixer is clean and free from contamination before use.
5. Follow plant safety and lockout/tagout procedures during maintenance.

6. Batch Preparation

6.1 Material Verification

1. Verify material identification labels.
2. Confirm batch numbers and quantities according to the production formulation.
3. Check materials for contamination, moisture, or lumps.

6.2 Weighing: Accurately weigh all materials according to the approved batch formulation.

Table1.5: Material Required Quantity

Material	Required Quantity
HDPE MA180	As per formulation
Calcium Carbonate	As per formulation
Zinc Oxide	As per formulation
UV Stabilizer	As per formulation
Carbon Black	As per formulation

Record all weights in the batch manufacturing record.

7. Mixing Procedure

Step 1: Equipment Preparation

1. Inspect the roller mixer.
2. Ensure the mixer chamber is clean and dry.
3. Start the mixer and verify proper operation.

Step 2: Charging HDPE MA180

1. Load the weighed HDPE MA180 into the roller mixer.
2. Run the mixer for approximately 2 minutes to distribute the base resin evenly.

Step 3: Addition of Calcium Carbonate

1. Gradually add the weighed calcium carbonate while the mixer is running.
2. Add slowly to prevent dust formation and material agglomeration.
3. Continue mixing for 4 minutes to achieve preliminary dispersion.

Step 4: Addition of Zinc Oxide

1. Slowly add the weighed zinc oxide into the mixer.
2. Ensure even distribution throughout the material bed.
3. Continue mixing for 2 minutes.

Step 5: Addition of UV Stabilizer

1. Add the measured UV stabilizer uniformly across the mixer.
2. Avoid dumping the entire quantity at one location.
3. Continue mixing for 2 minutes to ensure proper distribution.

Step 6: Addition of Carbon Black

1. Add carbon black last to prevent contamination and ensure better color dispersion.
2. Add gradually while the mixer is rotating.
3. Continue mixing for the remaining 4 minutes.

8. Total Mixing Time

Table1.6: Total Mixing Time

Stage	Time (Minutes)
HDPE MA180 pre-mixing	2
Calcium Carbonate Mixing	4
Zinc Oxide Mixing	2
UV Stabilizer Mixing	2

Carbon Black Mixing	4
Total Mixing Time	**14 Minutes**

9. Quality Checks

After completion of mixing:

1. Inspect the blend visually for uniform color.
2. Check for the absence of carbon black streaks.
3. Verify there are no lumps or unmixed filler particles.
4. Ensure additives are evenly dispersed throughout the batch.
5. Collect a representative sample for quality control testing if required.

10. Discharge Procedure

1. Stop the mixer after the total mixing time of 14 minutes.
2. Open the discharge outlet.
3. Transfer the mixed compound into designated containers or feeding hoppers.
4. Label the batch with:
    - Batch Number
    - Date
    - Operator Name
    - Material Identification

Conclusion: Following this 14-minute roller mixer procedure ensures uniform dispersion of HDPE MA180, calcium carbonate, zinc oxide, UV stabilizer, and carbon black, resulting in a consistent and high-quality compound suitable for further processing

8. HDPE MA180 Compound Development

To evaluate the effect of varying concentrations of Calcium Carbonate ($CaCO_3$), Zinc Oxide (ZnO), UV Stabilizer, and Carbon Black on HDPE MA180 compound properties.

Base Resin: HDPE MA180

Specimen Size: 500 g HDPE per specimen

Table1.6: Formulation Details

Specimen	HDPE (g)	$CaCO_3$ (g)	ZnO (g)	UV Stabilizer (g)	Carbon Black (g)	Total Weight (g)
1	500.0	15.0	2.5	2.5	2.5	522.5
2	500.0	20.0	5.0	5.0	5.0	535.0
3	500.0	25.0	7.5	7.5	7.5	547.5
4	500.0	25.0	10.0	10.0	10.0	555.0
5	500.0	30.0	12.5	12.5	12.5	567.5

Table1.7: Percentage Calculation

Specimen	$CaCO_3$ (%)	ZnO (%)	UV Stabilizer (%)	Carbon Black (%)
1	3.0	0.5	0.5	0.5
2	4.0	1.0	1.0	1.0
3	5.0	1.5	1.5	1.5

4	5.0	2.0	2.0	2.0
5	6.0	2.5	2.5	2.5

Table1.8: Total Chemical Consumption

Material	Total Quantity Used
HDPE MA180	2500.0 g (2.500 kg)
Calcium Carbonate	115.0 g
Zinc Oxide	37.5 g
UV Stabilizer	37.5 g
Carbon Black	37.5 g

Table1.9: Grand Total Batch Weight

Material	Weight (g)
HDPE MA180	2500.0
Calcium Carbonate	115.0
Zinc Oxide	37.5
UV Stabilizer	37.5
Carbon Black	37.5
Total Compound Weight	**2727.5 g**

Total Compound Weight = 2.7275 kg

Based on 2.5 kg HDPE:

Table1.10: Average Chemical Loading

Material	Quantity (g)	Average Loading (%)
Calcium Carbonate	115.0	4.60
Zinc Oxide	37.5	1.50
UV Stabilizer	37.5	1.50
Carbon Black	37.5	1.50

Table1.11: Material Summary for Production

Material	Quantity Required
HDPE MA180	2.500 kg
Calcium Carbonate	0.115 kg
Zinc Oxide	0.0375 kg
UV Stabilizer	0.0375 kg
Carbon Black	0.0375 kg
Final Compound Output	**2.7275 kg**

Five HDPE MA180 trial specimens were prepared using additive concentrations ranging from 0.5% to 2.5% for Zinc Oxide, UV Stabilizer, and Carbon Black, and 3% to 6% for Calcium Carbonate. The total material consumption for the complete trial was 2.7275 kg, comprising 2.5 kg HDPE and 227.5 g of additives. This report can be used as the official chemical calculation sheet for laboratory trials and production optimization.

9. Mould of Specimen

25mm*150mm, Height 2mm

88mm Diameter, Height 15mm

Mechanical and Physical Properties of Mild Steel (MS) for Mould Making

Sr. No.	Property	Symbol	Typical Value	Unit
1	Density	ρ	7850	kg/m^3
2	Young's Modulus	E	200–210	GPa
3	Poisson's Ratio	ν	0.27–0.30	–
4	Yield Strength	σy	250–350	MPa
5	Ultimate Tensile Strength	UTS	400–550	MPa
6	Elongation at Break	ε	20–30	%
7	Hardness	HB	120–180	Brinell (HB)
8	Shear Modulus	G	75–80	GPa
9	Bulk Modulus	K	140–170	GPa
10	Thermal Conductivity	k	45–55	W/m·K
11	Specific Heat Capacity	Cp	470–490	J/kg·K
12	Coefficient of Thermal Expansion	α	$11–13 \times 10^{-6}$	/°C
13	Melting Point	Tm	1425–1540	°C
14	Electrical Resistivity	ρe	1.43×10^{-7}	Ω·m
15	Machinability	–	Good	–
16	Weldability	–	Excellent	–

17	Corrosion Resistance	–	Moderate	–

Chemical Composition of Mild Steel (Typical)

Property Requirement	Mild Steel Performance	Remarks
Machinability	High	Easy to machine complex mould cavities
Strength	Moderate to High	Suitable for low to medium production moulds
Thermal Conductivity	Moderate	Ensures uniform heat distribution
Wear Resistance	Moderate	Can be improved by surface hardening
Weldability	Excellent	Easy repair and modification of moulds
Cost	Low	Economical compared to tool steels
Surface Finish	Good	Can achieve smooth mould surfaces

10. Mixing of Material

Figure1.10: Mixing of Material

Figure1.11: Injector industry Setup

Figure1.12: Blower Setup

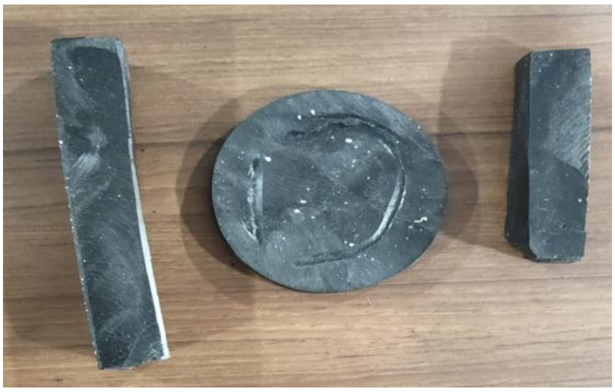
11. Specimen Photos

Specimen-1

Specimen-2

Specimen-3

Specimen-4

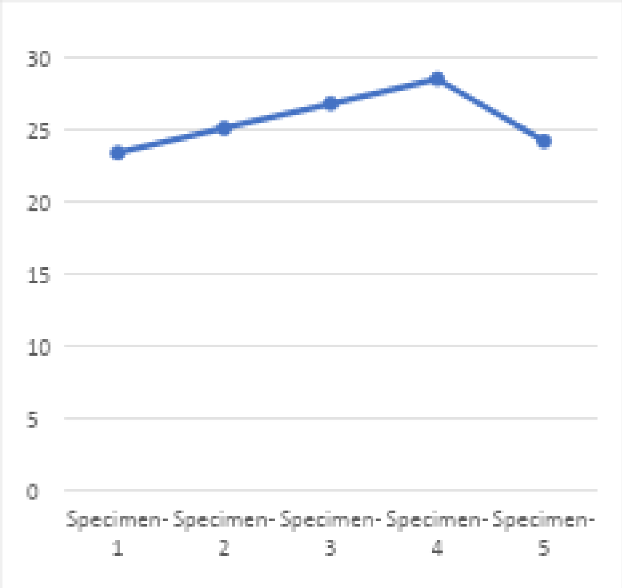


Specimen-5

12. Testing of Specimen

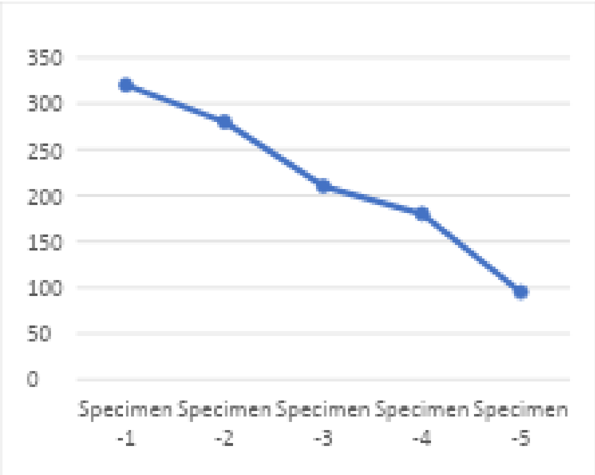
13. Results and Discussion

Property	Specimen -1	Specimen-2	Specimen-3	Specimen-4	Specimen-5
Tensile Strength (Mpa)	23.4	25.1	26.8	28.5	24.2
Elongation at Break (%)	320	280	210	180	95
Density kg/m³	944.2	946.8	949.1	950.8	953.4
MFR g/10 min	0.38	0.36	0.35	0.342	0.31
Carbon Black Content (%)	0.52	0.98	1.46	2.58	3.12
Flexural Strength (Mpa)	27.8	29.2	31.4	33.2	34.8
Flexural Modulus (Mpa)	980	1050	1120	1180	1250
Izod Impact (Notched) (J/m)	85	92	98	105	110
Shore-D Hardness	65	65	66	67	68



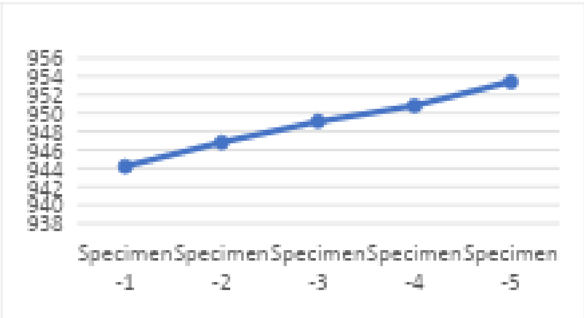
Graph1: Tensile Strength (MPa)

The tensile strength gradually increases from 23.4 MPa (Specimen-1) to 28.5 MPa (Specimen-4), indicating improved load-bearing capacity with increasing carbon black content. However, Specimen-5 shows a reduction to 24.2 MPa, suggesting that excessive carbon black adversely affects tensile performance.



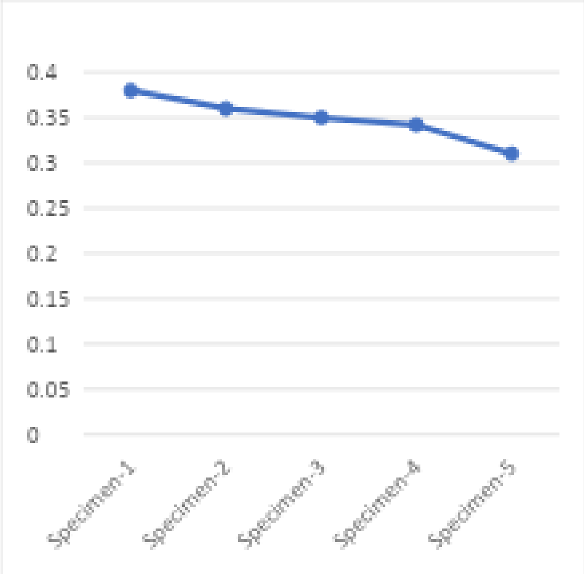
Graph2: Elongation at Break (%)

Graph 7 Illustrated Elongation at break continuously decreases from 320% (Specimen-1) to 95% (Specimen-5). This indicates that increasing carbon black content enhances stiffness but reduces ductility, making the material less flexible.



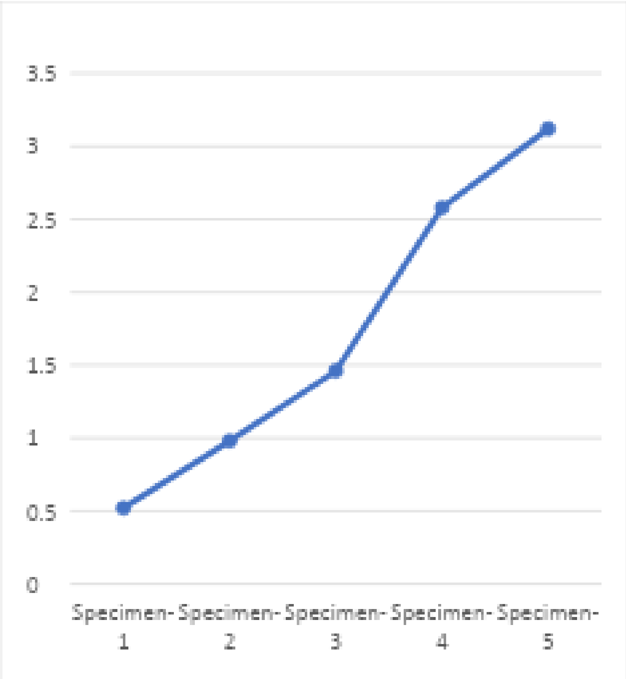
Graph3: Density kg/m³

The density increases steadily from 944.2 kg/m³ in Specimen-1 to 953.4 kg/m³ in Specimen-5. This trend confirms that higher filler loading results in a denser composite structure due to improved packing of material constituents.



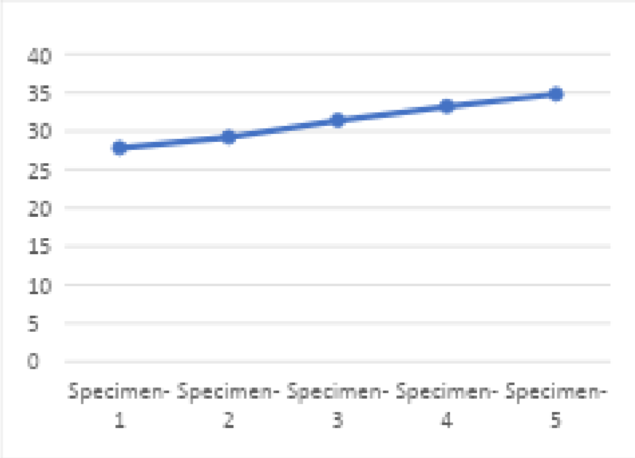
Graph4: MFR g/10 Min

The melt flow rate decreases gradually from 0.38 g/10 min to 0.31 g/10 min across the specimens. Lower MFR indicates increased melt viscosity caused by higher carbon black content, reducing polymer flow during processing.



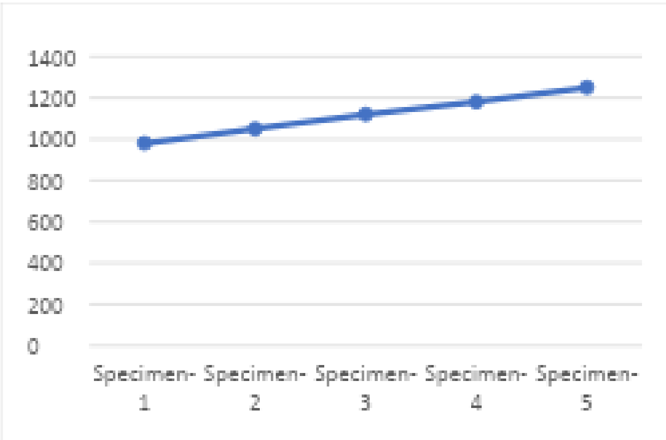
Graph5: Carbon Black Content (%)

Carbon black content increases progressively from 0.52% in Specimen-1 to 3.12% in Specimen-5. This confirms the intended formulation variation and directly influences the mechanical and physical properties of the HDPE composites.



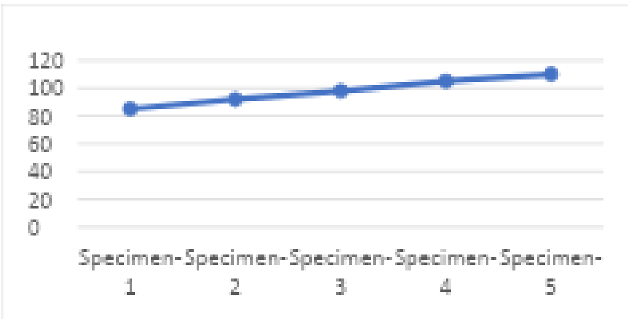
Graph6: Flexural Strength (MPa)

Flexural strength increases consistently from 27.8 MPa to 34.8 MPa as carbon black content increases. Specimen-5 exhibits the highest flexural strength, demonstrating enhanced resistance to bending loads due to improved reinforcement.



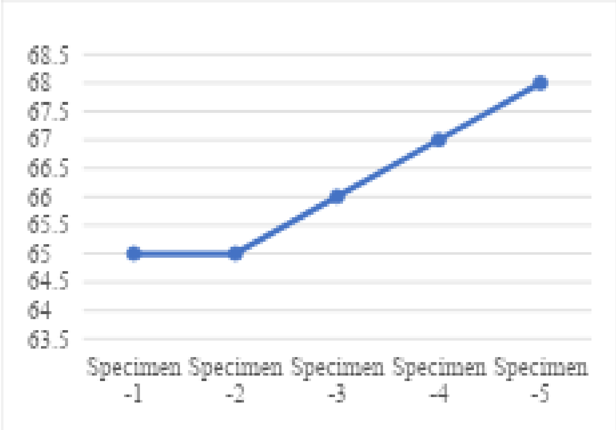
Graph12: Flexural Modulus (MPa)

The flexural modulus increases from 980 MPa in Specimen-1 to 1250 MPa in Specimen-5. This indicates that the composites become progressively stiffer with increasing carbon black concentration, improving structural rigidity.



Graph13: Izod Impact (Notched) (J/m)

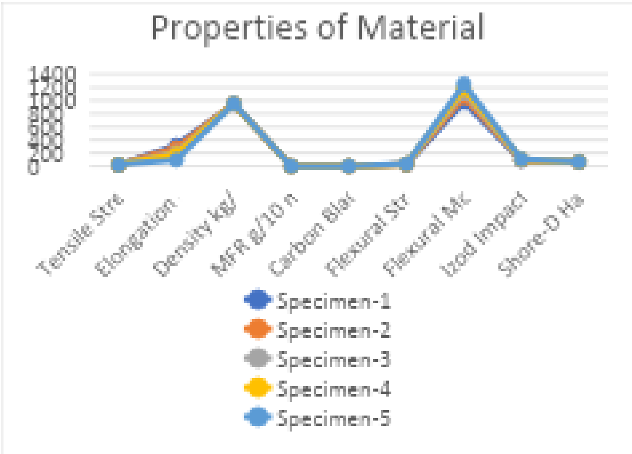
Impact strength increases steadily from 85 J/m to 110 J/m across the five specimens. Specimen-5 exhibits the highest impact resistance, indicating better energy absorption capability under sudden loading conditions.



Graph14: Shore D-Hardness

Shore-D hardness increases from 65 in Specimen-1 to 68 in Specimen-5. The results show that increasing carbon black content enhances the surface hardness and wear resistance of the HDPE composite.

Comparative Analysis of All Properties



Graph15: Comparative with all Properties of Materials

The comparative graph shows that density, carbon black content, flexural strength, flexural modulus, impact strength, and hardness increase progressively from Specimen-1 to Specimen-5. In contrast, elongation at break and melt flow rate decrease, while tensile strength reaches its optimum at Specimen-4 before declining in Specimen-5, indicating that excessive carbon black loading reduces tensile performance despite improving stiffness and hardness.

14. Conclusion

Based on your six-month progress report, the experimental work has focused on the development of composite HDPE materials reinforced with Calcium Carbonate ($CaCO_3$), Zinc Oxide (ZnO), UV Stabilizer, and Carbon Black for Floating Photovoltaic (FPV) structures intended for farm pond applications. Five different specimens were successfully prepared by varying the additive concentrations from 3–6% $CaCO_3$ and 0.5–2.5% ZnO, UV Stabilizer, and Carbon Black while maintaining HDPE MA180 as the base material. A standardized 14-minute roller mixing process was established to ensure uniform dispersion of fillers and additives, followed by mould preparation and specimen fabrication for subsequent mechanical and physical property evaluation. The developed specimens exhibited good surface quality, uniform color distribution, and appropriate dimensional stability, indicating the feasibility of producing composite HDPE materials suitable for floating solar applications.

The experimental investigation demonstrates that the incorporation of $CaCO_3$ improves stiffness and dimensional stability, while ZnO, UV Stabilizer, and Carbon Black significantly enhance UV resistance, thermal stability, and long-term environmental durability of the HDPE matrix. The developed composite material possesses desirable characteristics such as lightweight nature, high buoyancy, corrosion resistance, and excellent weatherability, which are essential for FPV structures operating in farm pond environments. Therefore, the proposed composite HDPE-based floating PV structure shows strong potential as a sustainable, economical, and durable solution for renewable energy generation and water conservation. Future work will focus on detailed mechanical characterization using ASTM standards, optimization of additive composition, and structural validation of the floating platform under actual operating conditions.

The comparative evaluation of all five HDPE composite specimens shows that the incorporation of carbon black significantly influences the mechanical and physical properties of the material. As the carbon black content increases from 0.52% (Specimen-1) to 3.12% (Specimen-5), the density, flexural strength, flexural modulus, impact strength, and Shore-D hardness improve consistently, indicating enhanced stiffness, strength, and durability. Conversely, the elongation at break and melt flow rate decrease progressively, reflecting reduced flexibility and processability.

Among all the specimens, Specimen-4 exhibits the best overall balance of properties, achieving the highest tensile strength (28.5 MPa) while maintaining excellent flexural and impact performance. Although Specimen-5 provides the maximum stiffness, hardness, and impact resistance, its lower tensile strength and significantly reduced elongation indicate that excessive carbon black loading adversely affects ductility. Therefore, Specimen-4 is identified as the optimum composition, offering the most suitable combination of strength, toughness, and structural performance for HDPE-based floating solar applications.

Acknowledgment

I would like to express my sincere gratitude to all those who have supported and guided me throughout the completion of this project titled ***"Development and Characterization of HDPE Composite Floating Photovoltaic Structures: Performance Optimization and Reliability under Multi-Environmental Loading"***

Declaration

I further declare that this project work has not been submitted elsewhere for the award of any other degree, Diploma, or certification. The information and data presented in this report are true and authentic to the best of my knowledge.

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