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3D Printing of a Tidal Turbine Blade Using Two Methods of SLS and FFF of a Reinforced PA12 Composite: A Comparative Study

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Abstract: This study scrutinizes the thermomechanical dynamics of 3D-printed hydrofoil blades utilizing a carbon and glass bead-reinforced thermoplastic polymer. Comparative analyses underscore the pivotal role of polymer reinforcement in augmenting mechanical strength and mitigating deformation and residual stress. The investigation elucidates the expeditious and cost-efficient manufacturing potential of low-cost Fused Filament Fabrication (FFF) printers for small-scale blades, revealing exemplary mechanical performance with nominal deflection and warping in the PA12-CB/GB printed blade. A comprehensive juxtaposition between Selective Laser Sintering (SLS) and FFF printing methods favors SLS due to its isotropic properties, notwithstanding remediable warping. Emphasizing the rigorous marine environment, the study cautions against the anisotropic properties of FFF-printed blades, despite their low mechanical warping. These discernments contribute to hydrofoil design optimization through numerical analysis, shedding light on additive manufacturing's potential for small blades in renewable energy, while underscoring the imperative for further research to advance these techniques.

Keywords: 3D printing; Tidal blade; Selective laser sintering (SLS); Fused filament fabrication (FFF)

1. Introduction

Tidal energy emerges as a critical asset for coastal nations such as Morocco [1,2], offering a pathway to sustainable power by tapping into the continuous ebb and flow of tides, propelling clean and dependable electricity generation for a resilient and environmentally friendly energy landscape [3,4]. In response to escalating energy needs, the utilization of tidal turbines becomes imperative, particularly with small horizontal axis tur-

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bines (HATT) or vertical axis turbines (VATT) designed to function in shallower and less robust currents [5–7]. The significance of these compact marine turbines lies in their cost-effectiveness, simplified manufacturing processes, and accelerated production, thereby supporting isolated communities in their quest for efficient electricity generation. The fabrication of such turbines can be achieved through advanced techniques like 3D printing or additive manufacturing (AM) [8–10], facilitating the automated construction of 3D components by layering base materials and overcoming limitations in molding fabrication methods [11,12]. Rouway et al. [13] investigate the viability of employing 3D printing technology, specifically Selective Laser Sintering (SLS), to create compact tidal turbine blades suitable for deployment in rural regions. The study focuses on utilizing specific polymers and reinforcements in the printing process, the research evaluates thermomechanical performance, revealing differences in warpage among materials. Ultimately, the findings emphasize 3D printing as a promising avenue for designing and developing efficient tidal energy systems, particularly favoring polyamide 12 reinforced with glass beads for minimal warpage. Also, in another work, Rouway et al. [14] evaluate the thermomechanical capabilities of a 3D-printed tidal turbine using Digimat-AM. They also utilize an alternative printing method, Fused Filament Fabrication (FFF). The study highlights the enhanced mechanical performance of a PEI-CB/CF blade compared to PA6-CB/CF, underscoring the 3D printing technology's potential in manufacturing small blades for green energy applications.

However, the particles are crucial for reinforcing composites, boosting their mechanical properties and overall performance [15,16]. Their strategic incorporation enhances strength, stiffness, and durability, improving the material's resistance to deformation and fracture. This reinforcement also extends to thermal and electrical conductivity, making composites versatile for diverse applications. The size and shape of particles, whether micro or nanoscale, influence the material's behavior, allowing for tailored properties. In addition, biocomposites with thermoplastic polymers and natural fibers replace non-biodegradable materials in wind turbine blades [17]. Rouway et al. [18] utilize the Mori-Tanaka approach to investigate how the elastic properties of composites are affected by the volume fraction and aspect ratio of carbon nanofillers such as CNTs and graphene. The results indicate improved performance when nanofillers are incorporated, resulting in increased Young's modulus and decreased Poisson's ratio. Additionally, distinct enhancements are noted in various orientations for polymers reinforced with CNTs and graphene nanoplatelets (GNPs).

Momeni et al. [19] found that the development of plant leaf veins follows an optimized pattern to fulfill biological functions and withstand environmental loads. Mimicking this structure, a 4D-printed wind blade exhibits improved strength, stiffness, and fatigue life. Galves et al. [20] identify the hexagonal infill pattern as effective in tidal turbine blade construction, Providing a substitute for the traditional shell-spar framework. Ramírez-Elías et al. [21] analyzed 3D-printed wind turbine ribs using PLA and CF-PLA materials, revealing higher compression strength with built-in holes. Arivalagan et al. [22] innovated a micro wind turbine blade utilizing 3D printing technology and PLA material, designed specifically for low-wind-speed scenarios. Arivalagan et al. [23] presented a printing technique using low-energy electron beam curing to enhance lightning protection on GFRP wind turbine blades. Findings indicated that the incorporation of a printed carbon fiber mesh successfully mitigated damage caused by simulated lightning strikes, ensuring the maintenance of structural integrity with a residual strength of 90.1%. Ming et al. [24] explored the application of a 3D printed continuous carbon fiber (CCF)/epoxy mesh with self-heating properties for deicing purposes. The printed mesh exhibited stable resistance after undergoing hot-cold cycles and demonstrated an 85% reduction in deicing time compared to glass fiber-reinforced composites. In a separate investigation, Kim et al. [25] investigated the incorporation of an optical fiber sensor into a turbine blade made of 3D-printed Ni-alloy. This allowed accurate temperature monitoring up to 500°C using directed energy deposition (DED) printing. The adoption of a strategy involving "line-by-line printing and stop" effectively reduced thermal energy accumulation, demonstrating the feasibility of monitoring high temperatures in complex metal structures.

Recycled composite waste transforms into 3D printing filaments, presenting an environmentally friendly alternative. This sustainable approach aims to diminish the ecological footprint and encourage circular practices in manufacturing, thereby supporting the conservation of resources [26]. The utilization of repurposed composites contributes to the development of inventive and functional products. In addressing the challenge of wind turbine blade composite waste, Rahimizadeh et al. [27] propose a recycling solution utilizing 3D printing technology. According to their study, incorporating recycled material into polylactic acid (PLA) filaments results in increased specific tensile strength and modulus when compared to PLA samples without recyclate. The validity of this recycling method was confirmed through thermogravimetric analysis and micro-computed tomography, suggesting the potential to create environmentally friendly materials with enhanced mechanical properties. Furthermore, Rahimizadeh et al. [28] present a recycling approach that employs mechanical grinding and 3D printing to improve the mechanical characteristics of 3D printed parts by integrating reinforcement fibers sourced from decommissioned turbine blades. The outcomes indicate a 16% enhancement in elastic modulus and a 10% elevation in ultimate strength, underscoring the viability of environmentally sustainable utilization of materials from retired wind turbine blades. Meanwhile, Tahir et al. [29] concentrate on the effect of recycled fiber categories on the tensile behaviors of 3D-printed PLA specimens derived from wind turbine blade waste, revealing that ground fibers exhibit higher ultimate tensile strength, while pyrolyzed fibers display elevated stiffness values. The alignment of micromechanical models with experimental results offers valuable insights into the effects of recycled fibers on material properties.

2. Materials and Methods

2.1 Materials

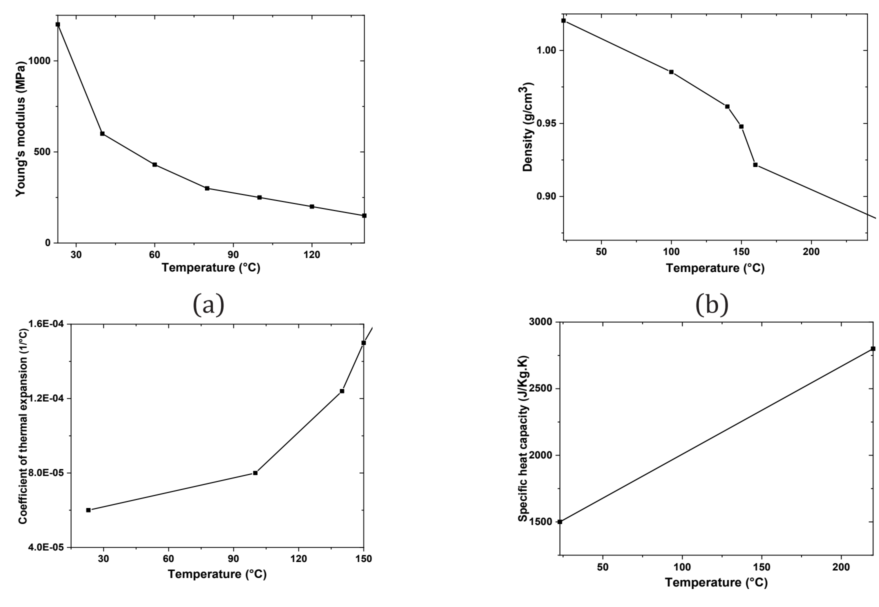
The Fused Filament Fabrication (FFF) and Selective Laser Sintering (SLS) printing methods make use of PA12 thermoplastic polymer, chosen for its high strength and recyclability. These technologies are employed for printing tidal turbines, utilizing both unreinforced and reinforced PA12 polymers with carbon (CB) and glass (GB) beads. Figure 1 illustrates the thermomechanical properties of PA12 concerning temperature, including Young's modulus, density, specific heat capacity, and thermal expansion coefficient (CTE). Refer to Table 1 for further details. Additionally, Table 2 presents the thermomechanical properties of CB/GB fillers.

Table 1. Thermomechanical properties of PA12 polymer.

Properties	Values
Glass transition temperature T_g (°C)	49
Melting temperature T_m (°C)	180
Thermal conductivity (W/Kg.K)	0.3
Poisson ratio v	0.39

Table 2. Thermomechanical properties of CB/GB fillers.

Properties	Carbon Beads (CB)	Glass Beads (GB)
Density (g/cm^3)	1.78	2.54
Diameter (mm)	0.05	0.05
Young's modulus (´10^3 MPa)	230	72
Poisson's ratio	0.2	0.22
Thermal conductivity (W/m.K)	1.7	0.8
Specific heat capacity (J/Kg.K)	720	753
Coefficient of thermal expansion (´10^{-6} 1/°C)	2	6



(c) (d)

Figure 1. Thermomechanical properties of thermoplastic polymers.

2.2 Methods

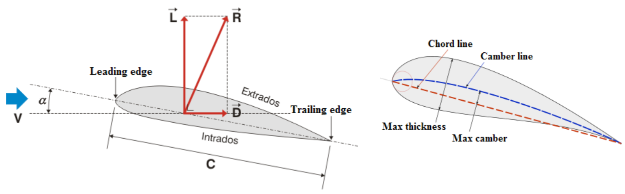
Aerodynamics and Geometry of the Hydrofoil

When a hydrofoil comes into contact with a water current, the hydrofoil's structure is influenced by the speed, creating a pressure difference between its upper (extrados) and lower (intrados) surfaces, as illustrated in Figure 2a. Typically, hydrofoils are designed to produce increased pressure, resulting in a force perpendicular to the relative velocity known as the lift force (L). At the same time, there is a force acting parallel to the direction of the relative velocity, caused by the hydrofoil's opposition to fluid movement, known as the drag force (D). These forces are commonly transformed into dimensionless parameters denoted as the lift coefficient (C_L) and drag coefficient (C_D), as articulated in equation (10).

$$C_L = \frac{L}{0.5\rho V^2 A} \text{ and } C_D = \frac{D}{0.5\rho V^2 A} \tag{1}$$

where ρ represents the density of seawater measured in (kg/m^3), V denotes the varying velocity of ocean currents expressed in (m/s), A represents the area of the hydrofoil blade measured in (m^2), and L and D refer to the lift and drag forces, respectively, measured in (N).

The hydrofoil utilized in this investigation was created by the IRDL laboratory team at ENSTA Bretagne. It involved modifying the configuration of a high-lift hydrofoil designed for low Reynolds number (Re=2.10^6) and possessing high lift capacity, similar to the WORTMANN (FX74-CL5-140). The refined hydrofoil, named NTS1020 (Nachtane-Tarfaoui-Saifaoui-1020), demonstrated optimal suitability for a marine current turbine as depicted in Figure 3. Noteworthy adjustments included a 10% increase in curvature and a 20% increase in thickness, as illustrated in Figure 2. Detailed dimensions of the hydrofoil are presented in Figure 5. The NTS1020 hydrofoil exhibited superior hydrodynamic performance, featuring a lower drag coefficient (C_D) and a higher lift coefficient (C_L) when compared to the reference hydrofoil (FX74-CL5-140). Notably, it showcased enhanced thickness in comparison to the FX74-CL5-140, contributing to the improved structural strength of the blade, as evident in Figure 4 and Figure 5. The profile, designed for printing purposes, possesses significant properties that necessitate experimental testing to comprehend the impact of printing on aerodynamic coefficients.



(a) (b)

Figure 2. Characteristic of the hydrodynamic profile (**a**). Thickness and curvature of the profile (**b**).

Source: [30].

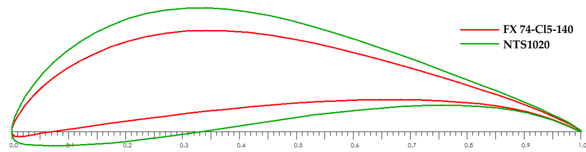
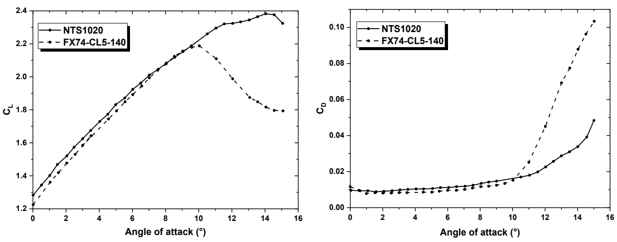


Figure 3. The geometry parameters of the NTS1020 hydrofoil compared to the FX74-CL5-140.



(a) (b)

Figure 4. Aerodynamic lift coefficients C_L (**a**) and drag coefficients C_D (**b**) as a function of angles of attack.

Selective Laser Sintering SLS process

The Selective Laser Sintering (SLS) process involves the fusion of thin layers of powder, typically 0.1 mm in thickness, distributed evenly across the construction area using a powder leveling roller. The part is fabricated within a sealed chamber filled with nitrogen gas to minimize oxidation and deterioration of the powder material. The powder on the build platform is maintained at an elevated temperature just below the melting point and/or the glass transition temperature T_g of the powder [31]. Infrared heaters are strategically positioned above the build platform to maintain a high temperature around the forming part and above the feed cartridges to preheat the powder before spreading it across the construction area. At times, resistive heating elements placed around the platform are utilized to heat the build platform. This preliminary heating of the powder and maintaining a consistent high temperature on the platform are essential to decrease the laser energy required for the process. The preheating phase reduces the laser energy needed for melting and serves to prevent distortion of the part during fabrication caused by uneven thermal expansion and contraction [32].

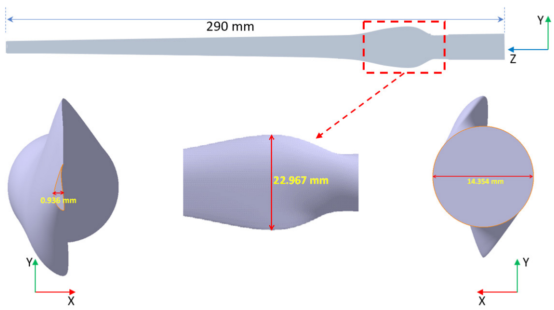


Figure 5. Geometric dimension of the blade.

After the formation and preheating of an appropriate powder layer, a focused CO_2 laser beam is employed to irradiate the powder bed. The beam is manipulated by galvanometers to thermally fuse the material, creating a cross-sectional slice. Following the completion of each layer, the build platform descends by a thickness corresponding to one layer, and a fresh layer of powder is applied and distributed employing a counter-rotating roller. The laser proceeds to survey the cross-sectional area of the following slice. This sequence repeats until the entire component is constructed, as depicted in Figure 6. A cooling phase is typically necessary to ensure uniform cooling of the parts to a temperature suitable for handling and exposure to ambient conditions. Premature exposure of components and/or the powder bed to room temperature may cause powder deterioration in the presence of oxygen, leading to uneven thermal contraction and consequent distortion of the parts. Ultimately, the components are extracted from the powder bed, cleaned, and subjected to finishing processes. The primary limitation of the SLS method stems from its elevated operating temperatures, which constrain its suitability for biodegradable materials [33].

The initial step in the 3D printing procedure involves creating the geometric design of a component using Computer-Aided Design (CAD) software. Subsequently, the design file undergoes conversion into the Stereolithography (STL) file format, a widely employed format compatible with various Additive Manufacturing (AM) machines. The design is subsequently sliced into thin layers by slicing software. Information about the part, such as layer thickness, toolpath, part orientation, material type, layer count, infill density, and pattern type, is required. This information is prepared in the slicing software and incorporated into the STL file. The file is then sent to the 3D printing machine and used as a command during the fabrication of the part. The additive manufacturing process has been summarized in eight steps, as illustrated in Figure 7 [34].

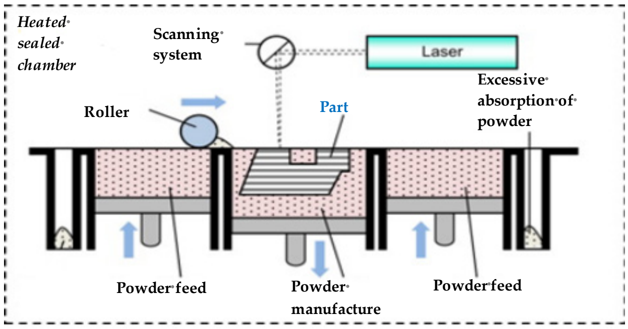


Figure 6. Diagram of the selective laser sintering (SLS) process.

Source: [35].

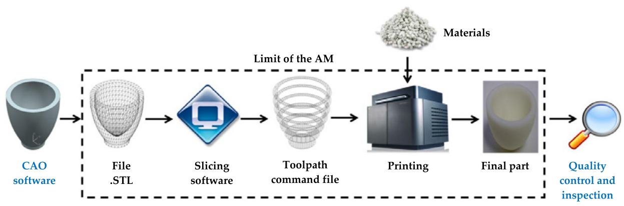


Figure 7. The additive manufacturing process chain.

Source: [34].

i. Mathematical Models for SLS

The fundamental equations describing the mechanical and thermal behavior of materials in liquid form during polymer melting, as well as the circulation of hot air in the printing chamber, are defined by the conservation laws recognized in the principles of mass, energy, and momentum conservation [36]. These equations are summarized as follows:

- **The continuity equation:**

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{v}) = 0 \tag{2}$$

- **The momentum equation:**

$$\frac{\partial(\rho \mathbf{v})}{\partial t} + \nabla(\rho \mathbf{v} \times \mathbf{v}) - \nabla(\mu_{eff} \nabla \mathbf{v}) = -\nabla p + \nabla(\mu_{eff} \nabla \mathbf{v})^T + S \tag{3}$$

- **The energy equation:**

$$\frac{\partial(\rho h)}{\partial t} - \frac{\partial p}{\partial t} + \nabla(\rho \mathbf{v} h) = \nabla\left[\left(\mu + \frac{\mu_t}{\sigma_t}\right)\nabla h\right] - S_h \tag{4}$$

with p being the pressure in (Pa), S representing the energy source, S_h being the volumetric heat flux in (kJ/m^3s), t denoting time in (h), and v indicating velocity in (m/s). Additionally, μ, μ_{eff}, and μ_t stand for viscosity, effective viscosity, and turbulent viscosity in (N.s/m^2), and h represents enthalpy in (J/kg). The notation ∇ signifies the divergence operator: $\nabla . u = \text{div u}$

The velocity gradient is simply a matrix of first-order spatial derivatives:

$v = [v_x, v_y, v_z]$:

$$\nabla \mathbf{v} = \begin{bmatrix} \frac{\partial \mathrm{v}_x}{\partial x} & \frac{\partial \mathrm{v}_x}{\partial y} & \frac{\partial \mathrm{v}_x}{\partial z} \\ \frac{\partial \mathrm{v}_y}{\partial x} & \frac{\partial \mathrm{v}_y}{\partial y} & \frac{\partial \mathrm{v}_y}{\partial z} \\ \frac{\partial \mathrm{v}_z}{\partial x} & \frac{\partial \mathrm{v}_z}{\partial y} & \frac{\partial \mathrm{v}_z}{\partial z} \end{bmatrix} \tag{5}$$

In the SLS additive manufacturing process, a heated powder layer is subjected to selective laser exposure, enabling the creation of three-dimensional solid components made of either polymer or metal. The key physical phenomena linked with the SLS approach involve heat transfer and powder sintering. The comprehensive modeling of the SLS procedure encompasses optical, thermal, and sintering aspects.

a. Optical Model

The manifestation of optical traits is evident as the laser beam engages with the surface of the powder bed. The optical framework takes into account different phenomena, including reflection, transmission, and absorption. In the SLS workstation, a resilient CO_2 laser is utilized as a source of thermal energy to initiate selective melting. Generally, laser energy is characterized by a significant thermal flux concentrated within a confined area. The pattern of laser intensity (I) across the beam diameter follows a Gaussian correlation [37]:

$$I(t, w) = (1 - R) I_0 \exp\left(-\frac{2r^2}{w^2}\right)$$

with:

$$I_0 = \frac{2P}{\pi w^2} \tag{6}$$

The reflectivity of the material surface is denoted by R. The maximum intensity of the beam, represented by I_0, is determined by the laser power (P) and the radius (w) of the laser intensity profile. The variable r signifies the radial distance measured from the central point of the laser beam.

b. Thermal Conductivity Model

The effective thermal conductivity k_e within the region is influenced by not just the temperature of the powder bed but also by various factors such as the thermal conductivity of the solid material (k_s), the thermal conductivity of the air (k_g), and the porosity (ϕ). Yagi-Kuni [38] has introduced a thermal conductivity calculation model that distinguishes between two temperature conditions: low and high temperatures. Under low-temperature conditions, thermal conductivity is predominantly affected by convection. Conversely, at high temperatures, the contribution of radiation to heat transfer becomes significant, consequently influencing thermal conductivity.

$$k_e = \begin{cases} k_s(1-\phi)/(1+\varphi k_s/k_g) & \text{for} \quad \mathrm{T} \le 673°K \\ (1-\phi)/\left[1/k_s + \varphi/\left(k_g + \varphi D_p h_{rs}\right)\right] + \phi D_p h_{rv} & \text{for} \quad T > 673°K \end{cases}$$

$$(W/m.°K)$$

with:

$$\varphi = 0.02 \times 10^{2(\phi - 3)} \tag{7}$$

The parameter φ is influenced by the material's porosity, represented by ϕ , and D_p denotes the diameter of the powder grains. The heat transfer coefficients related to radiation, h_{rs} and h_{rv} , apply to the powder grain's surface and the gaps between them, respectively.

c. Thermal Model

Thermal performance pertains to the mechanisms of heat transfer resulting from the infiltration of laser light into the powder bed. The thermal model encompasses phenomena such as conduction, convection, and radiation. In the SLS process, which focuses solely on an exterior heat flux (q) per unit incoming area into the body, the heat transfer characteristics can be elucidated using the fundamental equation of energy balance:

$$\int_\Omega \rho \dot{U} d\Omega = \int_S q dS \tag{8}$$

where ρ represents the effective density of the powder bed, while Ω denotes the volume occupied by the powder material with a surface area S. Equation (7) incorporates input parameters such as density, specific heat and thermal conductivity. It assumes an initial distribution of uniform temperature across the powder bed before the sintering process, set equivalent to the preheating temperature. The equation of heat transfer for the powder considers both radiation and convection mechanisms:

$$-k_e \frac{\partial T}{\partial z} = h\left(T_a - T\right) + \varepsilon_R \sigma_B \left(T_a^{\ 4} - T^4\right) \tag{9}$$

where T represents the powder bed temperature, T_a denotes the external environment temperature, h stands for the convective coefficient heat, ε_R signifies the material's surface emissivity, and σ_B represents the Stefan-Boltzmann constant.

d. Sintering Model

The sintering behavior typically pertains to the transformation of a material from a powdered state to a solid state during the sintering process, involving changes in the local powder density ρ [38]. The changing density of material over time is explained by the following differential equation that is dependent on time:

$$\frac{d\rho}{dt} = \left(\rho^{\max} - \rho\right) A \exp\left(-\frac{E}{RT}\right) \tag{10}$$

The symbol ρ^{max} represents the density of the solidified substance. The activation energy, denoted as E, is adjusted to a suitable value to ensure favorable sintering kinetics, taking into account the established parameters of the process. A represents the pre-exponential factor, which is unique to each material and is measured in units of s^{-1}.

ii. SLS Process Parameters

The manuscript employs Digimat-AM software, which offers thermomechanical analysis capabilities, for conducting numerical simulations pertinent to 3D printing. This software serves as a valuable tool for both printer manufacturers and end-users by facilitating the detection of manufacturing challenges. Through numerical simulation, hundreds of printing possibilities can be tested and studied prior to final blade production. Additionally, Digimat-AM autonomously computes the characteristics of reinforced polymers, leveraging the distinct thermomechanical attributes of polymers and filler particles/fibers via the Mori-Tanaka homogenization method. This approach streamlines the assessment and enhancement of 3D printed components, optimizing their performance and structural integrity.

The process of 3D printing, also known as Additive Manufacturing (AM), initiates with the creation of the hydrofoil profile-oriented blade structure through CAD design tools like CATIA. This investigation utilizes Digimat-AM to simulate diverse material setups, forecasting and evaluating the functionality of the manufactured components. Figure 8 outlines the sequential stages involved in digitally printing a tidal turbine blade. It is important to highlight that the success of 3D printing is contingent upon various factors including the specific process employed, the material used, thermomechanical constraints, and more. According to the scheme presented in Figure 8, the first step involves defining the geometry of the blade to be printed in the form of an STL file and the thermomechanical properties of polymer-based composites and particles. The thermoplastic polymer used is polyamide 12 (PA12) due to its biocompatibility for tidal applications. Afterwards, the blade's structure is modeled using the voxel technique for sequential printing. The printing procedure involves various variables, including tool path and specific inputs, to outline the manufacturing steps. Subsequently, the parameters of the additive manufacturing (AM) process are converted into a thermomechanical simulation, considering heat transfer mechanisms within the printing device. Following a finite element simulation, the outcomes are presented in the form of residual stresses using von Mises, temperature fields, deflection, and mechanical warping of the printed blade. The Selective Laser Sintering (SLS) process involves sintering plastic powder within the solid part. In this process, a laser source selectively melts the powder by scanning cross-sectional areas derived from the numerical model of the blade. Subsequent layers undergo sintering after the deposition of new powder, and this iterative process continues until the entire blade is printed. The parameters for the SLS printing process applied to the blade are detailed in Table 3, outlining the printing process's boundary conditions. These parameters are carefully determined and optimized to minimize warping and mechanical stresses. The blade is printed in a vertical orientation and is divided into three zones: the lower cylindrical zone (A), the twisted central zone (B), and the upper fine zone (C), as depicted in Figure 5. The blade experiences two stages during manufacturing—printing and cooling. Its thermomechanical behavior and warping are analyzed using Digimat-AM.

Table 3. SLS printing parameters for the blade.

Parameters	Values
Chamber temperature (°C)	330
Laser power (W)	48
Convection coefficient (W/m^2.°C)	15
Scanner spacing (mm)	0.15
Recovery time (s)	10
Scanning speed (mm/s)	12500
Beam diameter (mm)	0.5

Fused Filament Fabrication FFF

The Fused Filament Fabrication (FFF) process operates by extruding a thermoplastic polymer above its melting point. This method, widely employed due to its simplicity, affordability, and minimal waste, produces printed parts typically composed of pure thermoplastic material. Consequently, these parts exhibit characteristics such as low strength, rigidity, and compromised structural performance [39]. Mechanical properties of the fabricated components vary based on factors like filament material, extrusion process, and design parameters. The key components of an FFF printer include the heated extrusion head, nozzle, and build platform, with movement capabilities in three directions (x,y,z) and the option for heating. The extrusion head's movement in the (x,y), (x,z), or (y,z) directions influences print resolution (see Figure 9). Nozzle diameters range from 250 μm to 400 μm, while filament diameters typically measure 1.75 mm. The thermoplastic filament, heated just above its melting point, is fed into the extrusion head and then extruded through the nozzle onto the build platform. Step by step, this sequence recurs until the 3D model is finished. Solidification of the extruded filament occurs through cooling, ensuring precise control over pore size, shape, and homogeneity. The extruder comprises a cold end for filament intake and a hot end, typically aluminum, heated by a heating cartridge. This heating element melts the filament as it moves through the thermal tube toward the nozzle. A forced air cooling system, integrated with the print head, prevents excessive heat in extruder sections requiring lower temperatures.

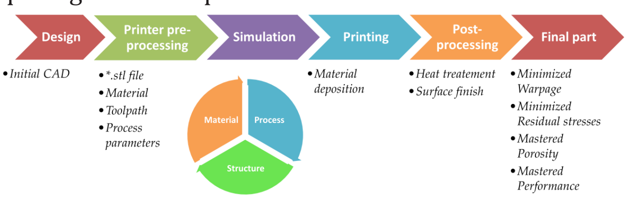


Figure 8. 3D Printing flowchart for the hydroturbine by Digimat-AM.

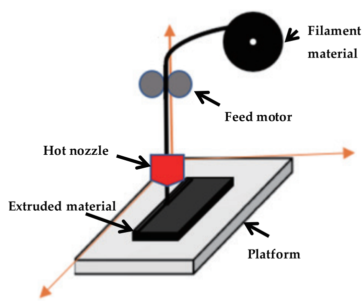


Figure 9. The Fused Filament Fabrication (FFF) manufacturing method.

Recent progress in additive manufacturing includes integrating strengthening substances into thermoplastic polymers to augment the mechanical characteristics of printed components. This enhancement involves introducing reinforcing fibers, like carbon and glass fibers, into polymer filaments. In a research conducted by Shofner et al. [40], an ABS matrix was employed to create nanofiber-reinforced composites through the FDM method. The filament comprised single-walled carbon nanotubes and ABS plastic. Following the filament's creation, a 40% improvement in tensile strength and a 60% increase in Young's modulus were observed in the printed parts.

This section elucidates the origin of distortion in printed components during the FFF printing process. When a heated thermoplastic layer is laid down, it undergoes a cooling and solidification process, leading to contraction. This layer is applied to a preceding layer that has already undergone cooling and contraction. The newly deposited layer adheres to a colder layer, and due to the differing rates of thermal expansion between the layers, they contract unequally until reaching thermal equilibrium. Consequently, the upper layer contracts in relation to the lower layer, generating residual thermal stress within the plastic layers [41]. The lower section of the upper layer experiences tension, while the upper part of the lower layer undergoes compression, resulting in shear stress at the layer interface. If these stresses surpass the mechanical strength of the component and the adhesion of the build plate, deformation occurs, as depicted in Figure 10a. Without proper protection against shrinkage, thermal contraction induces warping [42]. Alternatively, if the part is constrained by build plate adhesion, cooling leads to the development of thermal stresses rather than mechanical thermal deformation, as illustrated in Figure 10b.

The challenge of warping in 3D printing extends beyond mere avoidance of visible defects like edge cracking or deformation. High residual stresses resulting from warping can significantly compromise the strength of printed objects, as stressed interlayer bonding may break under mechanical load. Abrupt temperature changes during printing exacerbate stress concentration, leading to potential layer separation and altered fracture envelopes [9]. Addressing warping begins with filament selection, as filament properties interact with printing conditions to induce warping [43]. Materials with higher glass transition temperatures, such as ABS and polycarbonate, require elevated chamber temperatures to minimize thermal shrinkage and deformation. Professional FFF printers with heated build chambers offer an effective solution, maintaining temperatures below the material's glass transition temperature to reduce shrinkage and optimize part strength [44]. Specific chamber temperatures within the filament's creep zone are crucial, ensuring minimal warping and maximal part strength. For example, ABS performs well in an 85 °C chamber, while PLA benefits from a 35 °C chamber with adequate airflow for cooling during printing [44].

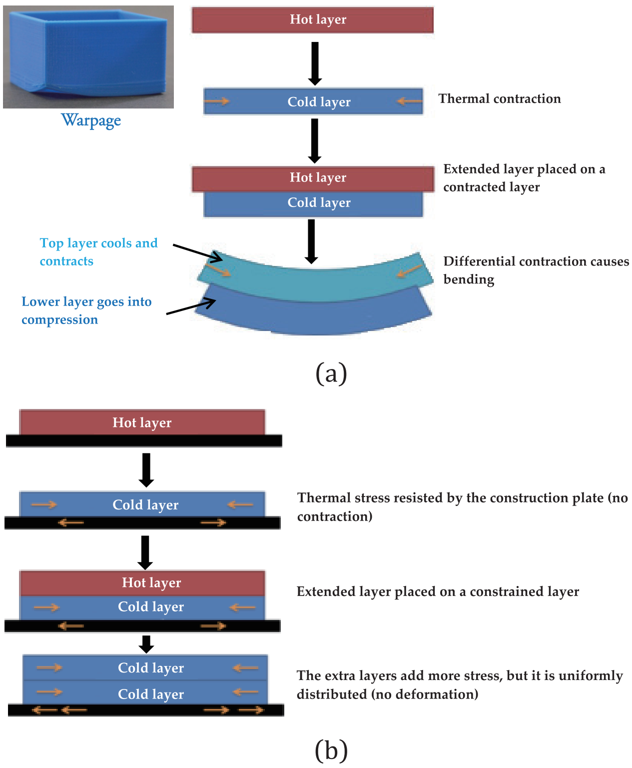


Figure 10. The deposited layers during printing. Poor adhesion (**a**) and adequate adhesion (**b**).

Filament selection for 3D printing is often driven by desired material properties, while integrating heated build chambers into printers presents ongoing challenges due to factors like patents and costs. Two main strategies address warping: adhesion surfaces, which mechanically secure prints but may not prevent delamination, and heated build plates, which enhance adhesion and minimize thermal shrinkage. However, maintaining an excessively high build plate temperature can exacerbate warping by softening the lower part of the print beyond its ability to resist stresses from cooler layers above. Temperature control is crucial, with heated build plate temperatures typically slightly higher than chamber temperatures due to measurement considerations and layer cooling during printing.i. Mathematical Models for FFF.

a. Mechanical Analysis

To utilize the finite element model in forecasting the thermo-mechanical characteristics of printed components, it becomes essential to articulate the constitutive equation dictating their mechanical response. The mechanical behavior of polymer composites under linear elasticity adheres to Hooke's law, which delineates the correlation between stress and strain in a subsequent manner:

$$\begin{pmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{12} \\ \gamma_{23} \\ \gamma_{31} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} \\ & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} \\ & & S_{33} & S_{34} & S_{35} & S_{36} \\ & & & S_{44} & S_{45} & S_{46} \\ & sym. & & & S_{55} & S_{56} \\ & & & & & S_{66} \end{pmatrix} \cdot \begin{pmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \tau_{12} \\ \tau_{23} \\ \tau_{31} \end{pmatrix} \tag{11}$$

where ε is the normal strain, γ is the shear strain, τ is the shear stress, and σ is the normal stress. Also, equation (11) can be rewritten in tensor notation as follows:

$$\langle \varepsilon_{ij} \rangle = S : \{\sigma_{ij}\} \tag{12}$$

No presumptions have been employed thus far, except elasticity. Therefore, equation (11) remains applicable to any anisotropic domain lacking symmetry elements.

For a material characterized as orthotropic, denoting a substance with three planes of symmetry that are mutually perpendicular, equation (11) transforms in the following manner:

$$\begin{pmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{12} \\ \gamma_{23} \\ \gamma_{31} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\ & S_{22} & S_{23} & 0 & 0 & 0 \\ & & S_{33} & 0 & 0 & 0 \\ & & & S_{44} & 0 & 0 \\ & sym. & & & S_{55} & 0 \\ & & & & & S_{66} \end{pmatrix} \cdot \begin{pmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \tau_{12} \\ \tau_{23} \\ \tau_{31} \end{pmatrix} \tag{13}$$

Equation (13) can be condensed with respect to the nine variables by taking into account the elastic constants, including Young's modulus (E_{ij}), Poisson's ratio (v_{ij}), and shear modulus (G_{ij}), in the following manner:

$$\begin{pmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{12} \\ \gamma_{23} \\ \gamma_{31} \end{pmatrix} = \begin{pmatrix} 1/E_{11} & -v_{12}/E_{11} & -v_{13}/E_{11} & 0 & 0 & 0 \\ & 1/E_{22} & -v_{23}/E_{22} & 0 & 0 & 0 \\ & & 1/E_{33} & 0 & 0 & 0 \\ & & & 1/G_{23} & 0 & 0 \\ & sym. & & & 1/G_{13} & 0 \\ & & & & & 1/G_{12} \end{pmatrix} \cdot \begin{pmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \tau_{12} \\ \tau_{23} \\ \tau_{31} \end{pmatrix} \tag{14}$$

with:

$$E_{11}=\frac{\sigma_{11}}{\varepsilon_{11}}\ ,E_{22}=\frac{\sigma_{22}}{\varepsilon_{22}}\ ,E_{33}=\frac{\sigma_{33}}{\varepsilon_{33}}$$
$$\nu_{12}=-\frac{\varepsilon_{22}}{\varepsilon_{11}}\ ,\nu_{13}=-\frac{\varepsilon_{33}}{\varepsilon_{11}}\ ,\nu_{23}=-\frac{\varepsilon_{33}}{\varepsilon_{22}}\tag{15}$$

And we have substituted:

$$S_{11}=\frac{1}{E_{11}}\ ,S_{12}=\frac{-\nu_{12}}{E_{11}}=\frac{-\nu_{21}}{E_{22}}\ ,S_{13}=\frac{-\nu_{13}}{E_{11}}=\frac{-\nu_{31}}{E_{33}}$$
$$S_{22}=\frac{1}{E_{22}}\ ,S_{23}=\frac{-\nu_{21}}{E_{22}}=\frac{-\nu_{12}}{E_{11}}\ ,S_{33}=\frac{1}{E_{33}}$$
$$S_{44}=\frac{1}{G_{23}}\ ,S_{55}=\frac{1}{G_{13}}\ ,S_{66}=\frac{1}{G_{12}}\tag{16}$$

By rephrasing equation (14), the stress matrix can be represented using the tensorial product of the stiffness matrix C and the strain tensor ε_{ij}:

$$\langle\sigma_{ij}\rangle=C:\{\varepsilon_{ij}\}\tag{17}$$

The compliance matrix S is derived by inversely transforming the stiffness matrix C, resulting in the subsequent matrix:

$$\begin{pmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\\ \tau_{12}\\ \tau_{23}\\ \tau_{31}\end{pmatrix}=\begin{pmatrix}C_{11} & C_{12} & C_{13} & 0 & 0 & 0\\ & C_{22} & C_{23} & 0 & 0 & 0\\ & & C_{33} & 0 & 0 & 0\\ & & & C_{44} & 0 & 0\\ & sym. & & & C_{55} & 0\\ & & & & & C_{66}\end{pmatrix}.\begin{pmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{33}\\ \gamma_{12}\\ \gamma_{23}\\ \gamma_{31}\end{pmatrix}\tag{18}$$

with:

$$C_{11}=\frac{\left(S_{22}S_{33}-S_{23}{}^2\right)}{S}\ ,C_{22}=\frac{\left(S_{11}S_{33}-S_{13}{}^2\right)}{S}\ ,C_{33}=\frac{\left(S_{11}S_{22}-S_{12}{}^2\right)}{S}$$
$$C_{12}=\frac{\left(S_{23}S_{13}-S_{12}S_{33}\right)}{S}\ ,C_{13}=\frac{\left(S_{12}S_{23}-S_{22}S_{13}\right)}{S}\ ,C_{23}=\frac{\left(S_{12}S_{13}-S_{11}S_{23}\right)}{S}$$
$$C_{44}=\frac{1}{S_{44}},C_{55}=\frac{1}{S_{55}}\ ,C_{66}=\frac{1}{S_{66}}$$
$$S=S_{11}S_{22}S_{33}+2S_{12}S_{23}S_{13}-S_{13}{}^2S_{22}-S_{23}{}^2S_{11}-S_{13}{}^2S_{33}\tag{19}$$

The determination of Young's modulus and Poisson's ratio can be achieved in the following manner:

$$E_{11}=\frac{\sigma_{11}}{\varepsilon_{11}}\ ,E_{22}=E_{33}=\frac{\sigma_{22}}{\varepsilon_{22}}$$
$$\nu_{12}=\nu_{13}=-\frac{\varepsilon_{22}}{\varepsilon_{11}}\ ,\nu_{23}=-\frac{\varepsilon_{33}}{\varepsilon_{22}}\tag{20}$$

The in-plane shear modulus can be determined from a specimen positioned at ± 45° by employing the subsequent equation.

$$G_{12}=\frac{E_{11}}{2\left(1+\nu_{12}\right)}\tag{21}$$

When it comes to polymers, the substance is recognized for displaying anisotropic characteristics, and the stress-strain response can be articulated in Cartesian coordinates as stated in [45]:

$$\varepsilon_{11}=\frac{1}{E}\left[\sigma_{11}\nu\left(\sigma_{22}+\sigma_{33}\right)\right]+\alpha_e\Delta T$$
$$\varepsilon_{22}=\frac{1}{E}\left[\sigma_{22}\nu\left(\sigma_{11}+\sigma_{33}\right)\right]+\alpha_e\Delta T$$
$$\varepsilon_{33}=\frac{1}{E}\left[\sigma_{33}\nu\left(\sigma_{11}+\sigma_{22}\right)\right]+\alpha_e\Delta T$$
$$\varepsilon_{xy}=\frac{1+\nu}{E}\sigma_{xy}\ ,\varepsilon_{xz}=\frac{1+\nu}{E}\sigma_{xz}\ ,\varepsilon_{yz}=\frac{1+\nu}{E}\sigma_{yz}\tag{22}$$

where α_ε is the coefficient of thermal expansion. The thermal deformation can be determined as follows:

$$\varepsilon_{th}=\alpha_e\Delta T\tag{23}$$

The effective stress σ_{eff} and von Mises stress σ_{Mises} can be calculated as follows:

$$\sigma_{eff}=\sqrt{\sigma_{11}{}^2+\sigma_{22}{}^2+\sigma_{33}{}^2}+2\nu\left(\sigma_{11}\sigma_{22}+\sigma_{11}\sigma_{33}+\sigma_{22}\sigma_{33}\right)$$
$$\sigma_{Mises}=\sqrt{\frac{1}{2}\left[\left(\sigma_{11}{}^2-\sigma_{22}{}^2\right)^2+\left(\sigma_{22}{}^2-\sigma_{33}{}^2\right)^2+\left(\sigma_{33}{}^2-\sigma_{11}{}^2\right)^2\right]}\tag{24}$$

b. Thermal Analysis

Thermomechanical analysis involves a sequential coupling of stress analysis and heat, establishing an indirect connection. In the numerical representation, the inclusion of heat transfer enables the computation of temperature fluctuations during the printing procedure. The governing partial differential equation governing heat transfer is articulated as follows:

$$\rho C_p\frac{\partial T}{\partial t}=k\left(\frac{\partial^2T}{\partial x^2}+\frac{\partial^2T}{\partial y^2}+\frac{\partial^2T}{\partial z^2}\right)\tag{25}$$

in which k (in W/m·K), C_p (in J/kg·K) and ρ (in kg/m^3)

express the thermal conductivity, specific heat capacity and the density of the polymer, respectively. The thermal energy H linked to the solidification of the phase is estimated in the following manner:

$$H = \int \rho C_p(T)dT \tag{26}$$

The layers in print were placed in the thickness orientation. A fresh layer, added at temperature T_m, undergoes cooling to match the chamber temperature T_c. Throughout the printing procedure, the layers experience heating through conduction, causing their temperature to surpass T_g. The thickness of the component is built up in the z-direction, maintaining a consistent chamber temperature T_c. In this dimension, the temporal evolution of temperature, denoted as $T(z,t)$, adheres to the subsequent thermal equation during time t:

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2} \tag{27}$$

The solution to this equation is as follows [46]:

$$T(z,t) = T_c + \frac{H}{\rho C_p} \frac{1}{\sqrt{\pi \kappa t}} \exp\left(-\frac{z^2}{4\kappa t}\right) \tag{28}$$

When κ is defined as k/ρ. C_p, representing the thermal diffusivity of the polymer in (m^2/s), and the printed component possesses considerable dimensions, particularly with a thickness e that surpasses the layer thickness Δe, the thermal energy of the layer can be acquired [47]:

$$H = \rho C_p \Delta e \left(T_m - T_c\right) \tag{29}$$

The method to acquire the temperature fluctuation across the thickness of the component is as follows:

$$T(z,t) = T_c + \left(T_m - T_c\right) \frac{\Delta e}{\sqrt{\pi \kappa t}} \exp\left(-\frac{z^2}{4\kappa t}\right) \tag{30}$$

where the initial state temperature is $T(z,t=0)=23$ ℃ . Equation (30) allows for the calculation of the temperature variation at the position z. For instance, to define the layer at which the temperature T is equal to T_g at a given time t during the printing process, one writes:

$$z(t) = 2\sqrt{\kappa t} \sqrt{\ln\left(\frac{\Delta e}{\sqrt{\pi \kappa}} \frac{T_m - T_c}{T_g - T_c}\right) - \ln \sqrt{t}} \tag{31}$$

This equation applies to the printing characteristics of materials. The resilience and dimensional consistency of printed components are influenced by residual stresses and warping introduced during the process. Wang et al. [48] formulated a straightforward analytical model, employing thorough simplifications, to forecast warping deformation following the FFF (Fused Filament Fabrication) procedure in ABS. They quantitatively scrutinized all contributing factors and obtained the subsequent expression for forecasting inter-layer warping δ_T:

$$\delta_T = \frac{3}{4} \alpha_e \left(T_v - T_c\right) \frac{L_i^2 \Delta e}{e^2} \left(1 - \frac{\Delta e}{e}\right) \tag{32}$$

where L_i represents the section length of the part, and $n=e/\Delta e$ represents the number of deposited layers. Derived from the examination of the model, some recommendations have been made to effectively reduce warping phenomena. According to this simple analytical model [47], the amount of deformation increases more than linearly with L_i, is proportional to the layer thickness Δe, and decreases monotonically with the increase in thickness e, meaning that warping is pronounced in the thin sections of the part. Additionally, the degree of deformation δ_T of the layer depends on the temperature gradient (T_g–T_c), as well as the coefficient of thermal expansion α_e, In accordance with the association outlined in equation (32).

ii. FFF process parameters

The performing hydrofoil profile NTS1020 is used to 3D print the blade using the FFF method [49]. FFF technology involves melting and extruding a polymer material filament to layer by layer print a part. The fiber aspect ratio is 10, and the reinforcements have a tensor with random orientation (a_{11}=0.33, a_{22}=0.33, a_{33}=0.33). The printer nozzle has multiple orientations during printing, but short fibers in the polymer tend to align with the printing direction [50]. Hence, the polymer's average fiber orientation is deemed to be random. In order to fabricate a component, the G-code must be derived from the geometric file in *.stl format. The G-code, produced by the Ultimaker 3 slicer software, includes directives for movement, extrusion, and heating. These commands are interpreted by the printer to create a 3D model. The Digimat-AM requires a toolpath based on the G-code, and the voxel method is utilized to mesh the blade. Following this, finite element analysis is employed to extract data related to residual stresses, temperature, and deformation fields in the modified blade.

3. Results and Discussion

The selection of the appropriate 3D printing technique depends on the specific requirements of your project and the allocated budget [51]. In the context of FFF printers, the resolution is contingent upon the nozzle size and the precision of extruder movements. Various factors, such as deformation, layer misalignment, shifting, and lower part shrinkage, contribute to decreased precision and surface smoothness of printed components. In contrast, SLS printers consistently yield objects with superior resolution compared to FFF printers, primarily determined by the optical spot size of the laser. Moreover, SLS printing exerts less force on the model, resulting in a much smoother surface finish. Additionally, the SLS method enables the production of intricate parts in a single process without requiring glue, unlike the FFF method, as powders function as a supportive structure for the printed components.

The Fused Filament Fabrication (FFF) technique is a prevalent technology in the consumer 3D printing sector due to its comparatively affordable nature. However, it comes with inherent technical limitations. In contrast, Selective Laser Sintering (SLS) printers are typically utilized in professional or industrial settings due to the higher cost of the machines. This cost is justified by the superior quality and technical capabilities of the printed components. Unlike the FFF method, the SLS approach doesn't necessitate structural support during printing, leading to shorter printing times. Post-processing for SLS-printed objects is less intricate compared to other technologies. It involves the removal of unused or unfused powder that acts as support during printing. This task can be carried out manually or with the use of compressed air. On the other hand, post-processing for FFF presents challenges. Inadequate dissolution of the support structure can potentially harm the print or result in surface imperfections. Moreover, specialized equipment such as glass containers or an ultrasonic bath is required [52].

The bonding strength between layers in SLS printing is very strong. This means that parts printed by SLS have almost isotropic mechanical properties. In FFF, printed objects are weaker in the vertical construction direction due to the anisotropy of material properties resulting from the additive layering method. FFF objects are anisotropic, and when weight is applied, these printed objects can be damaged if not oriented correctly. In short, FFF parts do not have the same strength in all directions, emphasizing the importance of orientation in the design and printing of robust parts.

Warping is a prevalent issue in the manufacturing process. As the material undergoes solidification through the FFF technique, a reduction in its dimensions occurs due to the cooling process. Since various segments of the printed object experience distinct cooling rates, their dimensions also alter unevenly. This non-uniform cooling results in the development of internal stresses, which subsequently cause the lower layer to be pulled upward, leading to warping. Similar to FFF, SLS objects are also prone to warping and shrinkage. The thermoplastic powder must be subjected to high temperatures for sintering, meaning the printed object undergoes a cooling process almost immediately after the formation of the solid layer. As the printed part cools, it contracts and shrinks in all directions, potentially resulting in imprecise dimensions. Stress due to contraction can also accumulate in certain parts of the printed piece, especially in corners and sharp edges, leading to warping or deformation of these areas.

Figure 11 presents a comparison during the printing and cooling processes between the SLS and FFF additive manufacturing methods of the printed blade based on mechanical deflection, residual stress, and warping. These thermomechanical properties were evaluated based on the volume fraction of carbon (CB) and glass (GB) particles with the PA12 polymer. According to the simulation results discussed earlier for both printing methods, a general conclusion can be drawn that increasing the volume fraction of particles increases von Mises residual stress, leading to a decrease in the mechanical deflection and warping observed in the printed component. Also, the mechanical response of the FFF-printed blade during printing is much more significant than that with SLS printing for mechanical deflection and von Mises residual stress (Figure 11) due to the high printing speed and significant mechanical forces demonstrated by the FFF method. However, the opposite is observed for the mechanical warping of the PA12-CB/GB-based blade, where it is more significant for the SLS method than for the FFF method (Figure 12). The addition of CB/GB particles can generate a uniform cooling rate throughout the blade, and the shrinkage of the blade becomes uniform, reducing warping, and indicating the dominant effect of these particles in resisting sample shrinkage. As the volume fraction of CB/GB particles increases, the coefficient of thermal expansion (CTE) decreases, resulting in low mechanical warping of the blade, due to the proportional relationship between the CTE and warping as shown in equation 32.

It is observed in Figure 11 that the mechanical deflection of the printed blade decreases with increasing volume fraction due to the improvement in mechanical stiffness. However, residual stress increases with volume fraction due to the accumulation of temperature gradient during printing. On the other hand, the temperature of the blade at the final printing stage increases slightly, due to the improvement in the thermal capacity of the polymer by adding the particles. Thus, by using the particles, the coefficient of thermal expansion decreases, which reduces mechanical warpage. In addition, the deflection and residual stress have higher values during cooling than during printing. This is because the accumulated temperature gradient generates residual stress during printing, and when the blade cools, the temperature gradient decreases and mechanical shrinkage becomes significant, resulting in high deflection and high residual stress compared to printing.

The vol% refers to the volume fraction of carbon/glass particles. The effect of vol% on the results of this study is significant as it directly impacts the mechanical properties and performance of the composite material. A higher vol% typically leads to increased reinforcement within the composite, resulting in enhanced strength, stiffness, and other mechanical properties. The study likely explores various volume fractions to assess how they influence the structural integrity, durability, and overall performance of the 3D printed composite material, providing insights into the most suitable reinforcement content for optimal turbine blade construction.

Mechanical warping is connected to the temperature field experienced by the material during printing, and since PA12 undergoes a higher temperature during SLS printing than FFF printing [53], warping is more pronounced in SLS. The combination of the high temperature in the SLS build chamber and the additional heating due to the laser results in significant degradation of the entire PA12 material. Numerous investigations have demonstrated that the characteristics of PA12 degrade when subjected to elevated temperatures over prolonged durations. Polymer chain crosslinking leads to an increase in molecular weight, which raises the viscosity in the molten state of the material and decreases its yield strength and elongation at break [54].

The deformation of parts in FFF printing is attributed to the quick heating and cooling cycles of the feedstock material, resulting in the accumulation of residual stresses during part construction. Previous findings suggest that composites with low residual stresses tend to exhibit more warping, and conversely, those with higher residual stresses experience less warping. Consequently, the FFF process shows higher residual stress, as depicted in Figure 11, leading to reduced warping, as illustrated in Figure 12. To elaborate, FFF has a higher printing speed, and it is evident that shrinkage increases with the acceleration of printing speed across all composite materials. This indicates that residual stress escalates with printing speed [55]. In contrast, in SLS, the printing speed is lower compared to FFF, resulting in heightened mechanical warping of the printed blade in the case of SLS.

Shrinkage is described as a modification in dimensions, while warping is characterized by alterations in shape. The primary factor contributing to warping is the inconsistency in shrinkage. When a component uniformly contracts in all dimensions, it diminishes in size while maintaining its original form. Conversely, if specific elements of the component experience disparate rates of shrinkage, it gives rise to internal stresses. Should these stresses surpass the structural rigidity, deformation, known as warping, occurs in the object.

The tidal turbine blade can be subjected to extreme forces in the marine environment. The direction of the force $\overrightarrow{F}$ is probably vertical to the blade, representing the flow of marine currents. We depict two illustrative diagrams in Figure 13 showing mechanical delamination, which is low for the SLS method due to the high bonding strength between layers. In contrast, for the FFF method with weak bonds, the blade can quickly incur damage through delamination under vertical printing forces.

It can be concluded that it is better to print the blade using the SLS method despite the significant warping observed, which can be compensated for. The harsh nature of the marine environment where the hydrofoil blade is located imposes isotropic loads in all directions that the blade may experience, eventually leading to its damage. It is deduced that the FFF method should be avoided in the construction of these structures, despite its low mechanical warping, due to the anisotropic property of this method.

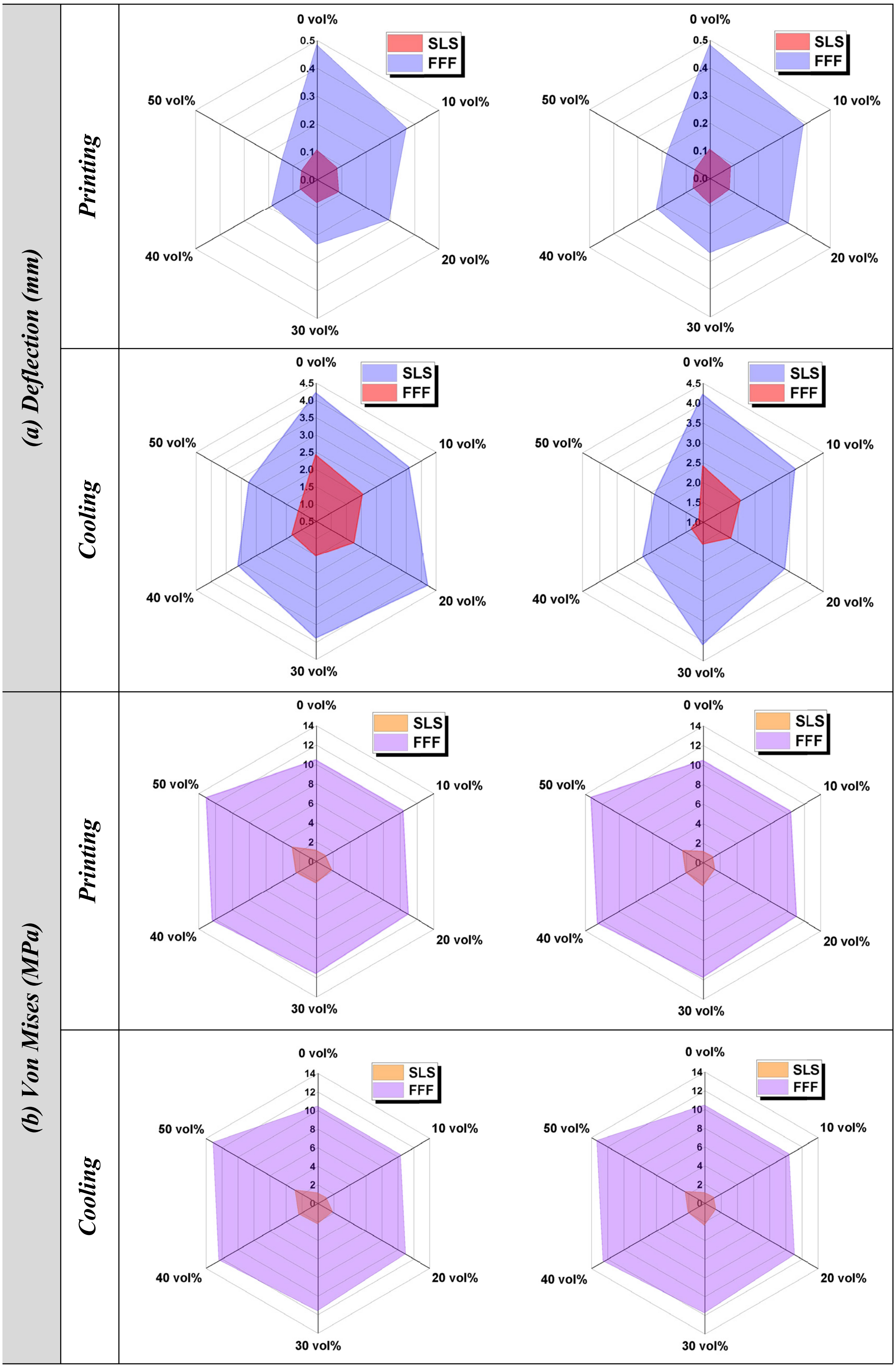


Figure 11. Comparison between the thermomechanical properties of the blade printed with PA12-CB/GB using SLS and FFF. Mechanical deflection (**a**) and von Mises residual stress (**b**).

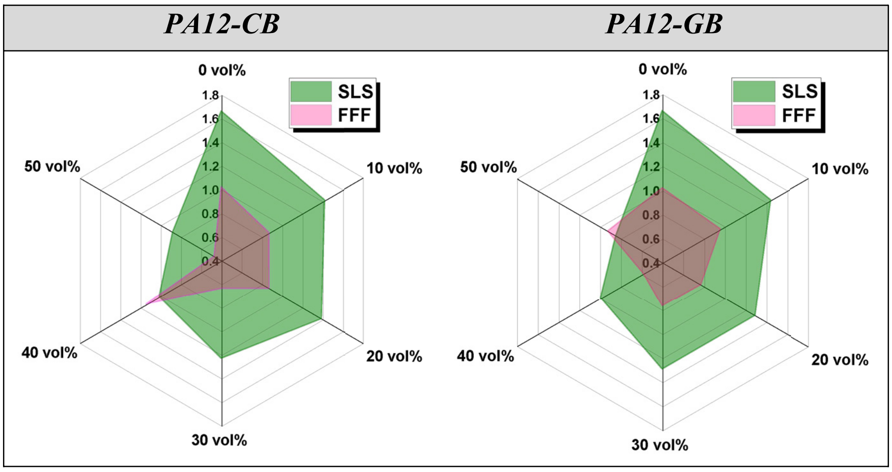


Figure 12. Comparison between the mechanical warping of the blade printed with PA12-CB/GB using SLS and FFF.

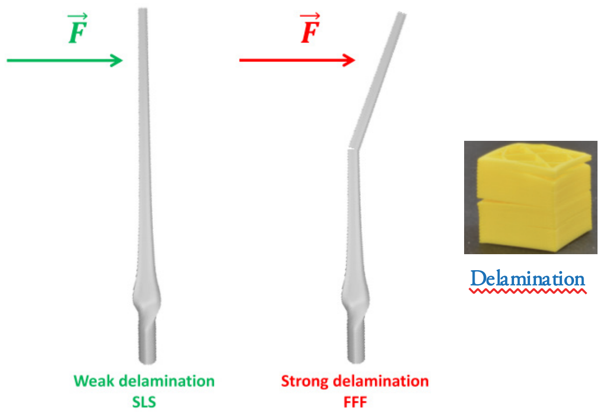


Figure 13. Comparison between the mechanical delamination of the blade printed with SLS and FFF.

4. Conclusions

The study delved into the thermomechanical characteristics of a hydrofoil blade produced through 3D printing. The utilized material is a thermoplastic polymer enriched with carbon and glass beads (CB/GB). Findings indicate that the deflection pattern undergoes changes with distinct printing materials. Additionally, an analysis is conducted to explore the impact of polymer reinforcement on mechanical strength concerning deformation and residual stress. Computational findings highlight the notable mechanical strength of reinforced polymers in comparison to their unreinforced counterparts. Furthermore, this reinforcement proves valuable in mitigating mechanical warping.

Furthermore, it can be inferred that the compact blade can be rapidly manufactured using economical FFF printers. The 3D printing procedure involves several phases and enhancements to achieve peak performance after numerous simulations. The thermomechanical effects were examined using improved thermoplastic materials. Simulation results revealed that the PA12-CB/GB printed blade displayed outstanding mechanical performance, characterized by minimal deflection and mechanical warping. Furthermore, a comparative analysis of two printing methods, SLS and FFF, was conducted. It was determined that employing the SLS method for blade printing is preferable due to the blade's isotropic properties, despite notable warping that can be rectified with particles. The marine environment, where the hydrofoil blade is situated, is known for its harsh conditions. The FFF-printed blade exhibits anisotropic properties, which are undesirable for these structures, despite having low mechanical warping. In conclusion, this numerical analysis offers optimization insights for hydrofoil design and demonstrates promise in printing compact blades. However, further research is necessary to advance additive manufacturing for the benefit of renewable energy applications.

Author Contributions

Marwane Rouway: investigation, methodology, and data curation, Mourad Nachtane: writing, reviewing, and original draft preparation. Mostapha Tarfaoui: supervision, writing, and validation. S. Jamoudi Sbai: data collection, conceptualization, and editing.

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Conflict of Interest

There is no conflict of interest.

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REVIEW ARTICLE

Trend Analysis of Marine Construction Disaster Prevention Based on Text Mining: Evidence from China

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Abstract: Global climate change has led to frequent natural disasters such as tsunamis and earthquakes, making offshore construction risky. In this paper, high-level papers from the Web of Science (WoS) were searched, and critical terms were identified and categorized using text-mining techniques. To ensure the resilience and safety of marine structures, we discuss the challenges of marine clays, marine eco-civilization construction, and disaster prevention databases. The recommendations presented provide valuable insights for engineers, researchers, and other stakeholders involved in marine construction projects.

Keywords: Text mining; Web of Science; Marine construction; Disaster prevention; Literature review

1. Introduction

Marine construction is a key global infrastructure sector, contributing significantly to economic development and trade [1]. However, the industry also faces inherent challenges, particularly regarding disaster preparedness. Natural disasters, such as hurricanes, tsunamis, and storm surges, pose a significant threat to marine structures, jeopardizing their integrity with severe economic and environmental consequences [2]. Between 1998 and 2017, tsunami losses totaled 251,770 people and $280 billion [3]. Over the past decade, the annual direct economic losses caused by marine disasters in China's coastal cities have reached an average of 10.004 billion yuan, with storm surges causing particularly serious losses, accounting for about 97% of the total [28]. With such disasters' increasing frequency and intensity, exploring innovative approaches and recent advances in disaster prevention in marine building construction has become imperative. In recent years, there has been a growing awareness of the vulnerability of marine structures and the need for solid disaster prevention measures, particularly in Indonesia, Sri Lanka, Thailand, and Maldives [4]. This awareness is underscored by the proliferation of high-

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level research articles available through platforms like the Web of Science [5]. These articles delve into many topics, including structural engineering, materials science, and environmental factors, and provide valuable insights into the marine construction industry's challenges [6-10]. Li-ping et al. [27] used seawater and coral sand instead of freshwater and river sand to prepare highly ductile cementitious composites and obtained good ductility and toughness. Døskeland et al. [29] found that response forecasting can improve the accuracy of weather-sensitive offshore construction decisions. Using calibrated noise loggers to characterize broadband noise levels and AIS data integrated with engineering records to characterize ship activity, Benhemma-Le et al. analyzed the large-scale response of harbor porpoises to piling and ship activity during the construction of an offshore wind farm [31]. Xu et al. [32] developed a four-quadrant conceptual framework for analyzing extended producer responsibility in offshore prefabricated construction, considering the scope and scale of responsibility and procurement methods. According to the latest Scopus data (21 March 2024), as shown in Figure 1, the literature related to offshore construction has expanded in size in nine years, from 517 to 665 per year.

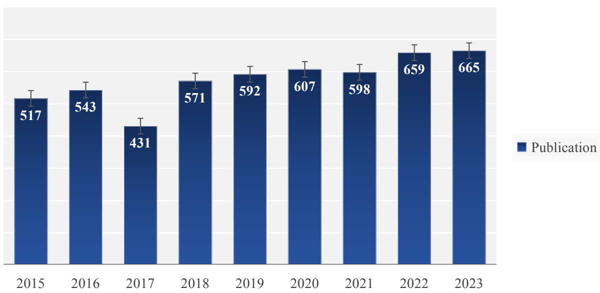

Figure 1. Annual number of offshore construction articles published.

As a result, many scholars have conducted literature reviews on offshore construction. Paiva et al. [30] analyzed the current state of scientific research on wave energy converters (WEC) through bibliometric methods. They found that Brazilian universities are leading in productivity, accounting for more than 36% of the scientific results on WEC. Amaechi et al. [31] analyzed trends in marine hose research through scientometrics analysis and found difficulties in the adaptation, acceptability, qualification, and deployment of marine hoses in the offshore marine industry. However, no study has comprehensively reviewed disaster reduction in offshore construction. This study aims to fill this gap. The study synthesizes and analyzes the vast amount of information available on the Web of Science, using text-mining methods to extract meaningful patterns and trends in disaster prevention strategies for marine building construction. This study is set in China, where it has completed many offshore construction projects. For example, the Penang Second Crossing Bridge in Malaysia, the longest cross-sea road bridge in Southeast Asia, was implemented by a Chinese company and is 22.5 kilometers long, with a total investment of about US$1.45 billion. Some of the projects currently under construction are shown in Table 1.

Table 1. Large offshore construction projects under construction in China.

Project Name	Descriptions
Carbon sequestration demonstration project for enping 15-1 oilfield	China's first million-ton offshore carbon sequestration demonstration project is located in the waters of the Pearl River Estuary. The project marks China's initial formation of drilling and completion technologies and equipment systems for offshore carbon dioxide injection, storage, and monitoring.
Enping 10-2 platform	China's first independently designed and built standardized unmanned platform with 20 sound slots and an oil and gas handling capacity several times that of traditional unmanned platforms.
Deep ocean one energy station	China's first independently designed and built 100,000-tonne, deepwater semi-submersible production and storage platform.
Floating offshore wind projects	China's first large-scale deep and distant sea offshore wind power project started in Wanning City, Hainan Province. With a total installed capacity of one million kilowatts, an average water depth of 100 meters, and a planned area of 160 square kilometers, the project is one of the world's most significant commercial floating offshore wind projects.

Note: All information from https://news.cctv.com/

The complexities inherent in marine building construction necessitate a comprehensive understanding of the challenges engineers, policymakers, and stakeholders face. From outdated design standards to environmental uncertainties, this paper aims to shed light on the multifaceted nature of disaster prevention in marine construction. The core research questions are as follows:

1). Which disasters are currently more frequent in offshore construction?

2). What research topics are popular in the field of disaster reduction in offshore construction?

3). How can current offshore construction disaster reduction practices be improved?

By consolidating information from high-level articles, we strive to offer a nuanced perspective on the current state of knowledge and explore recent advances that pave the way for more resilient and sustainable marine structures. Ultimately, this research contributes to the ongoing dialogue on disaster prevention, offering insights to inform future policies, practices, and innovations in marine building construction. The rest of this study is structured as follows: Section 2 describes the research methodology; Section 3 describes the results of the survey, including thematic analyses; Section 4 discusses the improvement strategies for offshore construction hazard mitigation and future research directions; and Section 5 concludes the study and points out limitations.

2. Materials and Methods

Referring to many reviews of text mining (TM) based approaches, the study is divided into five steps based on TM techniques [51,52].

1) Database Selection: Articles between the WoS data are recognized as high-level articles globally. Therefore, it is chosen as a database to collect relevant literature for this paper. Ensure that the quantity and quality of the literature are sufficient to support this study.

2) Literature Search: 168 kinds of literature were retrieved from the WoS database using the keywords "disaster prevention", "disaster", "marine construction", and "offshore construction" in combination with each other. After retrieval, the collected literature was initially screened according to Table 2, leaving those that fit the research theme and removing those that were irrelevant based on the relevance of the title and abstract. Then, further screening was done by reading the retained literature's full text to exclude literature irrelevant to the research topic or of low quality.

Table 2. Literature selection criteria.

Items	Criteria
Language	English
Area	China
Year	2015-2024
Article type	Research articles
Thematic relevance	Strong correlation

3) Data Extraction: Data and information related to the research topic, such as keywords, methods, results, etc., were extracted from the screened literature. Then, the extracted text data were cleaned and pre-processed to remove noise and irrelevant information and standardize the format.

4) Data Analysis: Analyses were performed using text mining tools and techniques with keyword extraction and topic construction [11,12]. The co-occurrence network in Figure 2 shows the main articles, with pink representing classic papers, green representing core papers, and cyan representing key papers. LDA analysis shows the current hot topics in marine building disaster prevention.

Figure 2. Related literature co-occurring network.

5) Trend Analysis: based on the results of the studies, improvement strategies for current marine disaster prevention and future research frameworks are proposed.

The LDA (Latent Dreichler Allocation) analysis used in this study is a statistical technique to reveal the hidden topic structure in a collection of text documents. It works on the assumption that each document is a mixture of multiple topics, and each topic is a distribution of words. By analyzing the co-occurrence patterns of words in a document, LDA can identify these potential themes and their prevalence in the corpus. Through this process, researchers can gain insight into the dominant and sub-themes present in the documents, which can lead to a deeper understanding of the themes and help to organize and classify large amounts of information.

3. Results

3.1 Common Hazards in Marine Construction

Many types of disasters are common in marine construction. The following Table 3 shows two cases of offshore construction accidents from the official website of the China Maritime Safety Administration:

Table 4 illustrates the climatic characteristics of the significant sea areas in China. Storm surge is the most critical disaster, particularly in offshore oil and gas exploration construction [35]. It is an abnormal rise and fall phenomenon of the sea surface caused by tropical cyclones, temperate cyclones, and cold tidal gales, which may trigger the influx of seawater into the land, leading to inundation and destruction [34]. The second is tsunami. It is undersea crustal movement caused by geological activities such as earthquakes, volcanic eruptions, or submarine landslides, which can generate massive waves and cause severe damage to marine construction [39,41]. The effective wave height in near-shore waters is usually greater than 2.5 meters. The third is red tide. It is a harmful ecological phenomenon in which marine plankton reproduces violently under certain conditions, causing seawater to change color. The fourth is an oil spill. It refers to accidents or operational errors during oil development, processing, storage, and transport, resulting in the leakage of crude oil or oil products into the sea [46]. The fifth is salt erosion and corrosion. Salts and chemicals in seawater may cause corrosion and damage to construction materials, increasing maintenance costs and cycles [40]. Finally, unstable submarine geological conditions may lead to settlement, sliding, or tilting of submarine structures, affecting the stability and safety of the project [36].

Table 3. Typical offshore construction accidents.

Item	Time	Description
Qingdao “4–27” ship pollution accident	27 April 2021, 8:51 am.	The Panamanian general cargo vessel SEA JUSTICE and the Liberian oil tanker A SYMPHONY collided when anchored in Qingdao Chaolian Island’s southeastern waters. As a result, the bow of the vessel “Yihai” was damaged, and the 2nd cargo hold on the port side of the vessel “Symphony” was broken; about 9,400 tons of cargo oil leaked into the sea, resulting in pollution of the sea area, which constituted a particularly major ship pollution accident.
Accident involving dredger Guangdong Zhongshan Gong 8666 in Guangzhou harbor.	6 May 2021, 9:10am to 9:30am.	When the dredger Guangdong Zhongshan Gong 8666 was dredging in Area A of the channel dredging project outside the mouth gate of Longdong Island, Nansha Harbor District, Guangzhou Harbor, two operators on board died of asphyxiation during the inspection of the second empty compartment on the port side of the vessel. The person in charge of the ship died of asphyxiation during the process of going down to the compartment to help the vessel, which resulted in a total of three deaths. The incident constituted a major water traffic accident.

Note: The above examples are from https://www.msa.gov.cn/

Table 4. Meteorological information for major Chinese seas.

Sea area	Climate Characteristic	Rainfall	Wind Speed	Temperature	Direction of Tides	Severity of Natural Disasters
East China Sea (including Yellow Sea and Bohai Sea)	Influenced by subtropical monsoons. Summers are rainy and windy, while winters are relatively dry.	Varied, higher in summer months, influenced by typhoons.	Moderate to strong, especially during typhoon season.	Varied, warm in summer, cool in winter.	Primarily follows the coastal contours.	Moderate to high risk, particularly during typhoon season.
South China Sea	Influenced by tropical monsoons. Hot and humid climate with frequent typhoons.	High, especially during summer and typhoon season.	Moderate to strong, with frequent typhoons.	Warm throughout the year.	Tidal currents are influenced by coastal geography and monsoon winds.	High risk due to frequent typhoons and storm surges.
North China Sea	Influenced by temperate monsoons. Summers are warm and rainy, while winters are cold and dry.	Moderate, higher in summer months.	Moderate to strong, influenced by monsoon winds.	Varied, warmer in summer, colder in winter.	Tidal patterns follow coastal contours.	Moderate risk, particularly during winter storms.

3.2 Popular Research Topics

In this study, the metadata was extracted with the help of WeiCiYun® with a total of 283,262 words, a size of 276.62 KB, 1296 valid entries, and 42,785 total words. Among them, the number of feature words is 1934. In this study, the first 50 keyword proper nouns are selected for co-occurrence, and the results are shown in Figure 3. Different colors in the graph represent different clusters [44]. The lines between each circular node represent the connection between each keyword. The size of the nodes also reflects the frequency of the keywords. The greater the frequency, the larger the diameter of the node [43].

Figure 3. Keyword co-occurrence network.

The number of topics was then chosen to be 6. Six core topic words were extracted, and the perplexity of the LDA model was 246.3. Table 5 shows the score for six theme words: "disaster database", "marine eco-civilization construction", "BIM/VR", "marine environmental air currents", "marine clay" and "dry work".

Table 5. Theme word score.

Topic Name	Item Count	Total Score	Average Score
Disaster database	126(9.72%)	77.83	0.62
BIM/VR	131(10.11%)	86.52	0.66
Marine eco-civilization construction	112(8.64%)	61.92	0.55
Marine environmental air currents	197(15.20%)	123.40	0.63
Marine clay	131(10.11%)	81.71	0.62
Dry work	130(10.03%)	70.49	0.54

Figure 4 shows the probability distribution of the relevant subject terms to visualize the study. The vertical coordinates in the graph represent the probabilities and the horizontal coordinates represent the number of lines of text in which the subject words are located.

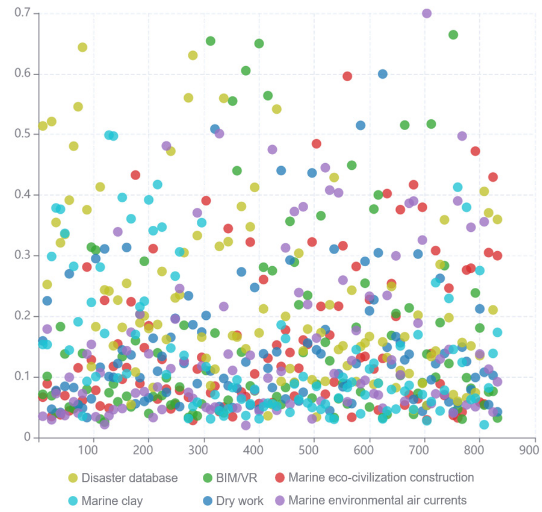

Figure 4. Probability distribution of topic words.

Disaster Database

Developing a database on offshore construction disaster preparedness begins with collecting comprehensive data on past offshore construction projects, including detailed information on environmental conditions, geological features, construction methods, and any accidents or disasters [13]. Utilize data from regulatory agencies, industry reports, and project documents. Incorporate information on structural design, safety protocols, and emergency response measures for various hazards. Include data on weather patterns, sea state, and any notable geologic challenges specific to each project site. Implement a standardized data structure and coding system to organize information uniformly [14]. Utilize a relational database management system for efficient data storage, retrieval, and analysis. Regularly update the database with new project data, incident reports, and lessons learned to continually improve disaster prevention strategies for offshore construction based on real-world experience. Collaborate with industry stakeholders to ensure that the database remains comprehensive and relevant and serves as a valuable resource for enhancing safety measures in future offshore constructions. Table 6 presents the databases used by the scholars.

Application of BIM and VR

Applying Building Information Modeling (BIM) and Virtual Reality (VR) to offshore construction disaster prevention requires the creation of a detailed BIM model of an offshore project that contains environmental and structural data [15,16]. This digital twin model can be used as the basis for VR simulations, allowing stakeholders to experience disaster scenarios and assess risk immersivity. VR-based simulation training can also be developed to train personnel in emergency response procedures to enhance preparedness. Real-time sensor data can be integrated into BIM models for continuous monitoring, and VR can provide immersive visualization of crucial parameters. Collaborative decision-making can be facilitated through VR platforms that enable stakeholders to discuss disaster preparedness strategies. the 4D capabilities of BIM help visualize construction sequences, while VR applications help identify safety issues and optimize the process. VR presentations allow stakeholders to learn about safety measures, and the iterative design process incorporates feedback from the VR simulation for continuous improvement. the combination of BIM and VR provides realistic simulations, improves communication, and facilitates the use of VR for constant improvement. The combination of BIM and VR provides realistic simulations, enhances communication, and promotes a collaborative, data-driven approach to offshore construction safety, improving disaster prevention.

Marine Environmental Air Currents

Marine environmental currents can significantly impact offshore construction by affecting construction activities' stability, safety, and efficiency. These currents, including prevailing winds and localized breezes, can present challenges during lifting and installation operations, affecting crane positioning, material transport, and construction vessel stability [17]. Winds can impose lateral loads on structures, making accuracy and control critical during critical construction phases [18]. In addition, the interaction of ambient air currents in the ocean with the complex geometry of offshore structures can create aerodynamic effects that must be carefully considered during the design and engineering process. Understanding and mitigating the impact of these currents is critical to ensuring the safety and success of offshore construction projects.

Marine Ecological Civilization Construction

Building a marine ecological civilization involves developing and implementing sustainable practices to ensure the health and balance of marine ecosystems. The concept emphasizes the harmonious coexistence of human activities with the marine environment and promotes responsible resource management, conservation, and environmental protection [19]. Efforts to build an ecological civilization of the oceans include the reduction of pollution, sustainable fisheries management, the protection of biodiversity, and the adoption of eco-friendly technologies in marine industries. It requires a holistic approach that considers the interconnectedness of marine ecosystems and recognizes the importance of ecological balance for the well-being of the environment and human societies dependent on marine resources [20]. International cooperation, regulatory frameworks, and public awareness play a crucial role in promoting an ecological civilization of the oceans that supports the long-term health and sustainability of the world's oceans.

Dry Work

In offshore construction, dry work is defined as activities performed on structures or components above the waterline that are not submerged in the marine environment [21]. This includes construction tasks performed in areas of an offshore facility that remain dry or above sea level under normal operating conditions. Dry operations include various activities such as welding, painting, equipment installation, and structural modifications that can be performed without direct contact with seawater. Unlike wet work, which involves underwater operations, dry work provides a more controlled and accessible work environment, streamlines the construction process, and ensures the efficiency and safety of the workforce. In recent years, research on dry operations for offshore construction has covered a wide range of fields, with the following research hotspots:

Table 6. Offshore construction disaster database.

Source	Database	Factors
[53]	296 major accidents and disasters from the World Offshore Accident Database (WOAD).	Concrete structures, loading buoys, and conduit racks.
[54]	1072 cases from the major European industrial accident databases ARIA (2006), FACTS (2006), MARS (2008), MHIDAS (2001), and TAD (2004), and the US National Response Centre (NRC) database (2008).	Earthquakes: peak ground motion parameters (peak ground acceleration (PGA), peak ground velocity, peak ground displacement) and spectral acceleration. Floods: height of inundation and velocity of water flow.
[55]	170,000 data from various hazards on offshore platforms in the Bohai Oilfield from 2012 to 2022 in CSV format.	Swaying of pipes and flanged joints caused by strong winds and waves; lack of warning signs, lights, and other necessary equipment.

1) Lightweight Repair Operations of Subsea Wellheads: Research focuses on maintaining and repairing subsea wellheads, including innovations in technology and equipment. Thomer [60] developed unique subsea transmitters and receivers to cover Dolphin Energy's 48-inch and 36-inch subsea pipelines; this allowed the pipelines to be decommissioned and isolated on the seabed so that repairs could be carried out in dry conditions.

2) Analysis and Numerical Simulation of Offshore Floating Wind Turbines: Researchers focus on the power response of floating wind turbines at sea to optimize design and operation. Yang et al. [61] investigated a new concept of motion stabilizer, a completely passive device consisting of several undulating plates.

3) General-Purpose FPSO Topside Modules: Researchers address principles and best practices for interfacing with Floating Production Storage and Offloading Vessel (FPSO) topside modules. Jin et al. [62] developed new procedures to provide a new concept of cumulative failure frequency for assessing the structural safety of upper modules.

4) Pile Sinking for Monopile Foundations for Offshore Wind Turbines: Research in this area focuses on the critical points of sinking pile construction for offshore wind turbine monopile foundations to ensure safety and stability. Liu et al. [63] developed a vibration model of a tubular pile in a marine pile sinking system and found that the energy dissipated by external damping can be reduced, and the efficiency of pile sinking can be improved by modulating the input frequency and optimizing the tubular pile structure.

5) Hydrogen Production from Offshore Wind Power: Researchers explore the technologies and paths for hydrogen production from offshore wind power to promote the use of renewable energy. Luo et al. [64] analyzed methods for hydrogen production from offshore wind power, including alkaline water electrolysis, proton exchange membrane water electrolysis, and solid oxide water electrolysis.

6) Deepwater Semi-Submersible Production Platform (DSPS) Column Oil Storage Structures: Research in this area is concerned with the structural design and application of deepwater DSPS platforms to meet energy needs. Chuang et al. [65] calculated the hydrodynamic response of a semi-submersible submersible to first- and second-order wave forces by combining three-dimensional radiation/diffraction theory and Morison's equations to develop a practical methodology for investigating the collision risk of risers.

Marine Clay

Marine clay, also known as marine sediment or sea mud, is a fine-grained sedimentary material that accumulates at the bottom of the ocean or other bodies of water [22]. It mainly comprises clay minerals, silt, and organic matter and is characterized by a smooth, sticky texture and high plasticity when wet [23]. Marine clay is deposited in low-energy aquatic environments where suspended particles settle slowly to form fine-layered sediments. Marine clay is a typical geological formation in coastal areas and continental shelves. It plays an essential role in various geotechnical and environmental processes, including forming sedimentary rocks, habitats for marine organisms, and essential materials in coastal engineering and construction projects. Marine clay significantly impacts offshore construction due to its unique geotechnical properties. When encountered in submarine sediments, marine clays can present challenges for foundation engineering, as their high plasticity and low shear strength can make it challenging to obtain a stable base for structures such as offshore platforms [24]. The viscous nature of marine clay also presents challenges for construction activities such as drilling, piling, and subsea excavation [25]. Over time, sediments' compressibility and consolidation potential can affect structures' long-term stability. In addition, the interaction between marine clays and offshore infrastructure can lead to problems such as foundation settlement or lateral movement. Engineers and construction planners must carefully evaluate and address these geotechnical issues when designing and implementing offshore construction projects to ensure marine structures' integrity, safety, and longevity [26]. Research on marine clay in recent years has focused on the following aspects.

1) Physical Properties of Seabed Sediments: Researchers have analyzed them from different sea areas in detail for their physical properties, including density, compressibility, and shear strength. These parameters are critical to the design and stability of marine engineering and subsea infrastructure. Shan et al. [56] conducted dynamic triaxial laboratory tests on man-made marine clays containing various clay minerals under the same test conditions and confirmed that clay minerals, especially montmorillonite, significantly affect the dynamic properties of large strains.

2) Microstructure and Thixotropy: The researchers conducted an in-depth study of the microstructure of marine clays to understand their thixotropic properties. Thixotropy is the transformation of soil from solid to fluid under stress. This is important for the safety and reliability of subsea engineering. Bo et al. [57] found that the modifiers affected the unconfined compressive strength of marine clays in the following order: potas-

sium hydroxide > silica > quicklime > burnt plaster.

3) Engineering Properties of Marine Clays: Researchers have explored the behavior of marine clays in different engineering environments, such as subsea anchoring, subsea pipelines, and subsea tunnels. They studied clays' deformation properties, strength, and stability to guide engineering practice. Sun & Yi [59] utilize incinerated bottom ash, waste marine clay, and ground granulated blast furnace slag as building materials.

4) Seafloor Geological Environment: The researchers have investigated the geological environment of different sea areas, including seafloor geomorphology, sediment types, and seismic activities. This helps to understand the formation and distribution of marine clays. Guan et al. [58] found that low sedimentation rates and hydrodynamic perturbations have a greater impact on sedimentary processes in marine clays than climatic fluctuations.

4. Discussions

Based on the results of the previous analyses, this study proposes the following future improvement strategies and research directions.

4.1 Conduct Thorough Construction Planning and Evaluation

Adequate planning and risk assessment are required before undertaking offshore construction. This includes a thorough understanding of the project objectives, geographical conditions, climatic features, and marine environment, and the use of modern technology and modeling tools to assess the potential impact of natural hazards such as storms and tsunamis that may be faced, as well as the potential implications of human factors such as vessel traffic and pollution [45]. Gaogeng et al. [38] are mainly focused on the prevention and control of severe weather, support structure damage, and seal integrity. At the same time, safety standards and precautions are implemented in cooperation with professional teams and local government authorities to minimize risks and ensure smooth construction.

4.2 Adopting Advanced Technologies and Materials

The government should vigorously promote high-quality materials such as carbon fiber composites, high-strength concrete, and corrosion-resistant steel, which are widely used in offshore buildings and have good compressive, tensile, and corrosion-resistant properties and can enhance the structural strength and durability of the building. Advanced construction technologies, including three-dimensional printing, modular construction, unmanned aerial vehicles, and robotics, can improve construction efficiency, reduce costs, and ensure construction quality, thus enhancing the disaster-resistant performance of offshore buildings. Ngo et al. [47] applied a probabilistic approach to calculate the scour depth (SD) and the probability of seismic events to establish a fragile surface at the base of a suction barrel. Finally, the damage probability of suction drum foundations for offshore wind turbines is obtained by combining the product of scour and seismic hazards and the fragility curves. Advanced construction technologies, including three-dimensional printing, modular construction, and drone and robotics, can improve construction efficiency, reduce costs, and ensure construction quality, thus enhancing the disaster resistance of offshore buildings. The integration of multiple sensing and communication technologies, such as Global Navigation Satellite Systems (GNSS), high precision leveling, seismic monitoring, physical datasets (including magnetometers, gravimeters, geo-electromagnetics, resistivity tomography, HPL data), and drones are highly conducive to early warning of hazards in offshore construction [50].

4.3 Establishing Environmental Monitoring and Early Warning Systems

To establish an effective environmental monitoring and early warning system, it is first necessary to deploy various sensors and monitoring equipment, including monitoring devices for marine meteorology, geology, and marine biology, to collect marine environmental data in real-time. Advanced data processing and analysis technologies are used to monitor and analyze these data in real-time and identify possible disaster risks. In the case of offshore wind farms, for example, geological drilling should be carried out at each turbine foundation location and analyzed and simulated accordingly to adjust the design parameters [42]. Finally, a sound early warning mechanism is established to issue timely warning information and remind relevant personnel to take countermeasures. At the same time, regular drills and training are conducted to ensure the effectiveness and reliability of the early warning system.

4.4 Developing Emergency Preparedness and Training

Establishing a sound emergency response plan for marine construction first requires a comprehensive assessment of all types of disaster risks that may occur and the formulation of corresponding disaster response measures and rescue plans. Subsequently, the emergency response organizational structure and command system must be established, and the duties and tasks of relevant personnel must be clarified. Conduct targeted training and drills to ensure that all relevant personnel understand the contents of the emergency response plan, familiarize themselves with the response process and operational procedures, and improve their ability and efficiency in responding to disasters. Regularly review and update the emergency response plan and adjust and improvements according to the actual situation to ensure its adaptability and effectiveness. Canada has introduced new legislation to increase the liability of offshore construction companies to C$1 billion, but liability for negligence will remain unlimited [48].

4.5 Enhancing Public Awareness and Participation

The key to strengthening public awareness of disaster prevention for offshore construction lies in carrying out extensive publicity and education activities, conveying to the public the importance and potential risks of offshore construction through various media channels, and guiding the public to realize the importance of disaster prevention. Sato & Nagatomi [37] identified the need for an international workshop venue at sea to collect various research results and discuss them cross-sectional. At the same time, relevant volunteer activities for environmental protection and disaster response should be organized to encourage the public to actively participate in marine environment monitoring, cleaning up marine rubbish, and supporting disaster rescue to make joint efforts to protect the marine ecological environment and achieve the goal of sustainable development [49].

4.6 Adopting a Whole-life Approach to Seawater Corrosion

Firstly, seawater-resistant low-alloy steel or other materials with good corrosion resistance should be used. These materials have better corrosion resistance in the atmospheric and splash zones and can extend the structure's service life. Secondly, coatings can prevent corrosion in the atmospheric and wave splash zones. Select coatings suitable for marine environments and regularly inspect and maintain them to ensure their effectiveness. Cathodic protection is also an effective anti-corrosion method to prevent localized and total corrosion. By applying an electric current, the metal surface of the structure is protected. In addition, corrosion prevention methods should be emphasized at the early stages of construction. For example, the recoating construction process of partial descaling plus top coating is adopted to extend the service life of primer, reduce descaling, and save money.

5. Conclusion

The world's increasing reliance on marine infrastructure underscores the urgent need for solid disaster prevention measures in marine building construction. As the frequency and intensity of natural disasters continue to grow, the challenges facing marine builders have never been more complex. This study examines the field's pressing issues and highlights recent advances that promise to mitigate these challenges. One of the primary challenges facing marine construction is the impact of climate change, which is causing sea levels to rise. Builders must now meet the need for structures to withstand the dynamics associated with these environmental changes. The second challenge is the increasing frequency and severity of hurricanes, typhoons, and cyclones. Constructing marine buildings that can withstand the destructive forces of these extreme weather events is a daunting challenge that requires innovative engineering solutions. The third is the constant threat to the integrity of marine structures posed by saltwater corrosion. Conventional building materials are susceptible to degradation over time, necessitating the development of corrosion-resistant materials to improve the corrosion resistance of structures.

Current breakthroughs in materials science have led to the development of high-performance corrosion-resistant materials explicitly designed for the marine environment. These materials enhance structural integrity and contribute to sustainable building practices. Secondly, engineers are adopting cutting-edge design principles that consider the dynamic nature of aquatic ecosystems. Floating structures, modular construction, and adaptive design are increasingly essential to provide resilience under changing environmental conditions. Indeed, by integrating remote sensing technology, marine structures can be monitored in real-time. This allows early detection of potential problems, facilitating timely maintenance and intervention to prevent disaster escalation. Advanced computer simulation and modeling techniques enable builders to assess the impact of various environmental conditions on marine structures. This allows for design optimization and enhances its ability to withstand extreme weather events and changing sea conditions.

In addition, there are limitations to this study. Since the literature was all from the Web of Science, future studies could consider additional literature sources such as PubMed, ScienceDirect, and Emerald as supplements.

Author Contributions

Yin Junjia: Conceptualization, Project administration, Methodology, Formal analysis, Investigation, Data curation, Visualization, Validation, Writing - original draft, Writing - review and editing. Aidi Hizami Alias: Conceptualization, Project administration, Supervision. Nuzul Azam Haron: Supervision. Nabilah Abu Bakar: Supervision.

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Data Availability

All study data were obtained from the cited bibliography.

Conflict of Interest

All authors disclosed no conflict of interest.

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RESEARCH ARTICLE

Global Distribution of Brachyuran Crabs in Mangroves

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Abstract: The present work has compiled a total of 389 brachyuran crab species belonging to 188 genera and 38 families to be present in mangrove forests across 122 countries/territories in 10 sub-regions of two global hemispheres *viz*., Indo-West Pacific (IWP) and Atlantic East Pacific (AEP). The mangrove crabs are highly diverse in the IWP as compared to AEP. They exceed 100 species in nine countries of the IWP *viz.*, Indonesia, India, Japan, Thailand, Australia, Singapore, Philippines, Malaysia, and China. The least number of mangrove crab species (> 10) are found to be present in 38 countries under the AEP. Four countries/territories do not have any record of mangrove crabs. Sesarmidae is the predominant family of mangrove crabs, followed by Ocypodidae and Portunidae. The present work also has brought out 818 synonyms, which otherwise interfere with the preparation of a checklist for an exact number of crab species. It is a matter of necessity to conserve the crabs, which are keystone species of the mangrove ecosystems.

Keywords: Mangroves; Brachyuran crabs; Keystone species; Species diversity; Occurrence and distribution; Checklist; Synonyms; Sesarmidae; Ocypodidae; Portunidae; IUCN; Indo-West Pacific; Atlantic East Pacific hemisphere

1. Introduction

Mangrove crabs are the “keystone” species of mangrove forest ecosystems, amazingly adapted to the fluctuating conditions and distributed in tropical and warm temperate latitudes lying between 32^0N and 38^0S [1,2]. They play a vital role in the structure and function of mangroves by processing the litter, producing the organic matter, releasing the nutrients, aerating the soil by bioturbation, determining the mangrove community structure by seed predation, creating the microhabitat for other fauna, serving as the food source to juvenile fishes, and contributing to the mangrove secondary production by faeces that form the basis of a coprophagous food chain [3,4,5].

The mangrove crabs are commercially valuable for

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human consumption especially the species of *Scylla, Portunus* and *Charybdis* belonging to family-Portunidae. *Scylla* species are mud crabs typically associated with mangroves in estuaries and sheltered coastal habitats in soft muddy bottoms where they dig deep burrows, while *Portunus* and *Charybdis* colonize in the coastal subtidal areas and are adapted to swimming with the last pair of pereiopods modified into flattened paddles. Sesarmidae are generally not commercially valuable; but, ecologically important for the productivity of mangrove and estuarine habitats [1,3].

Jones [1] was the first to provide a comprehensive review of mangrove crabs, describing the occurrence of 61 genera and sub-genera. This account is, however, grossly outdated. The checklists of mangrove crabs are available, but scattered from India [6–9], Brazil [10], Malaysia, Singapore [11], Australia [12] and America [13]. However, there is no consolidated account of the global distribution of mangrove crabs. Moreover, the species diversity of mangrove crabs in terms of the number of species is often varying, which is due to the presence of a large number of synonyms. Above all, most of the mangrove crab species are not properly assessed for IUCN categorization due to data deficits on their distribution.

A database on spatial distributions of mangrove crabs will be useful for updating the biodiversity as new taxa are increasingly described. Even after many taxonomic revisions [14–16], there are still several ambiguities and taxonomic issues that call for further studies on the mangrove crabs [17]. The database is also important in the present context of mangrove habitat loss. Even a small-scale change in the mangrove ecosystem affects the macro-faunal diversity and might even lead to the local extinction of a few species [18]. The mangrove crab checklist will be useful to assess the man-made pressures on biodiversity and also for sustainable management [19,20]. The global distribution, species richness and endemicity of mangrove crabs need to be understood for better biodiversity assessment and conservation prioritization. Hence, the present work has compiled baseline data for the global distribution of mangrove crabs to find out knowledge gaps for their conservation.

2. Materials and Methods

The present study collated data on the brachyuran crabs of mangrove habitats by using the Google search engine and literature databases 'Google Scholar', 'PubMed', 'Web of Science' and 'ScienceDirect'. The publications were searched by using key terms such as 'Mangrove crabs', 'Brachyuran crabs', 'Distribution & Occurrence of crabs', 'Keystone species', 'Crab Synonyms', 'Sesarmidae', 'Ocypodidae', 'Portunidae', 'IUCN Redlist'. Further search was made with the above-said terms in combination with Indo-West Pacific, and Atlantic East Pacific. Thus, the brachyuran crab species were searched extensively from the scientific literature for their occurrence in mangrove forests of different study areas/countries/sub-regions. Their distribution and synonyms were analysed from websites such as WoRMS—World Register of Marine Species (www.marinespecies.org) and GBIF Global Biodiversity Information Facility (www.gbif.org). The data are tabulated for the family, species, number of species and synonyms, frequency of occurrence in different countries and sub-regions. The ranges of species numbers are marked on the map for their global distribution. To find out the relationship between crab species diversity and mangroves, the data on plant species diversity or mangrove cover were obtained from the World Atlas of Mangroves [21].

3. Results and Discussion

Brachyuran crabs are the most diverse group of crustaceans due to their occurrence in almost all marine and terrestrial habitats in the world, and they are represented by 6,793 species under 1271 genera and 92 families [17]. As per our present compilation, the global mangrove habitats are represented by 389 species of brachyuran crabs belonging to 188 genera and 38 families across 122 countries/territories. Thus the mangrove habitats support 5.72% of species, 14.79% of genera and 41.3% of families belonging to brachyuran crabs that occur totally in all habitats on the earth.

Globally the mangrove crabs are distributed in two hemispheres viz., the Atlantic East Pacific and the Indo-West Pacific under 10 sub-regions viz., Eastern and Southern Africa, Middle East, South Asia, South-East Asia, East Asia, Australia and New Zealand, Pacific islands, North and Central America, South America, and West and Central Africa.

Crabs are highly diverse in the Indo-West Pacific (IWP) as compared to the Atlantic East Pacific hemisphere (AEP) (Figure 1, Figure 2). Among the countries, nine countries are represented with mangrove crabs exceeding 100 species. The countries are Indonesia (196 spp.), India (189), Japan (160), Thailand (153), Australia (146), Singapore (143), Philippines

(143), Malaysia (127), and China (116 spp.); and all these countries belong to the IWP. The lowest numbers of mangrove crab species (< 10) are in record of 38 countries under the AEP, in contrast to only 10 countries under the IWP. Similarly, the range of species is high in different sub-regions of the IWP. In contrast to these, the range of species is relatively low in different sub-regions of the AEP: 2–9 in West & Central Africa, 8–35 in South America, and 0–69 in North and Central America (Table 1). This is by Abele [22] who has recorded only 5 crab species associated with American mangroves.

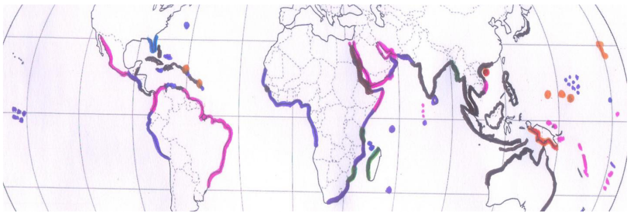

Figure 1. Global distribution of mangrove crabs (Black = >100 species, Red = 81–100, Green = 61–80, Purple = 41–60, Pink = 21–40, Brown = 11–20, Blue = 1–10, Orange = 0 species).

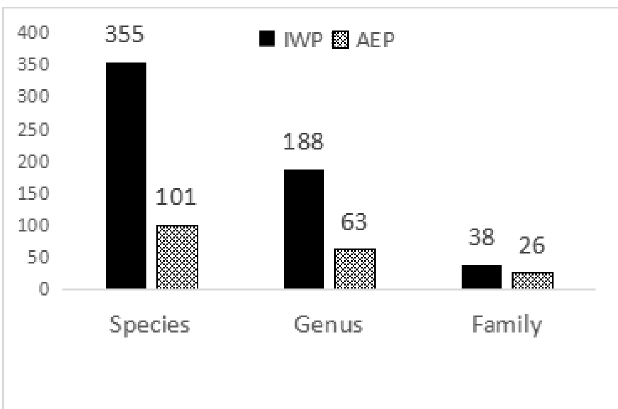

Figure 2. Number of crab species, genera and families distributed in hemispheres of Indo-West Pacific (IWP) and Atlantic East Pacific (AEP).

South East Asia which occupies 34.4% of the total global mangrove area is represented with the highest crab diversity. Indonesia is the country with the largest mangrove cover in the world, holding the highest number of 196 crab species. This supports the observation that the species richness of mangrove crabs is parallel to the area of mangrove forest cover or mangrove tree species [9,11].

We have also observed a significant correlation between mangrove crab diversity and mangrove plant diversity or mangrove area (Figure 3). However, such a relationship awaits confirmation by undertaking comprehensive surveys of mangrove crab assemblages over wider latitudinal gradients. India with the 10th largest mangrove area in the world is recorded with the second highest number of 189 crab species, and this is due to intensive surveys carried out in the country [8]. Hence, many studies are required for the preparation of comprehensive checklists of mangrove crabs in different countries. This deserves much attention in the present context of worldwide loss of mangroves, especially in Southeast Asia due to various stressors such as land conversion, increasing sea level rise, subsidence of coast-land by extraction of oil, gas and water, accompanied by land erosion and saltwater intrusion as well as the decline of sediment supply for mangrove colonisation as a result of damming of rivers and sediment mining.

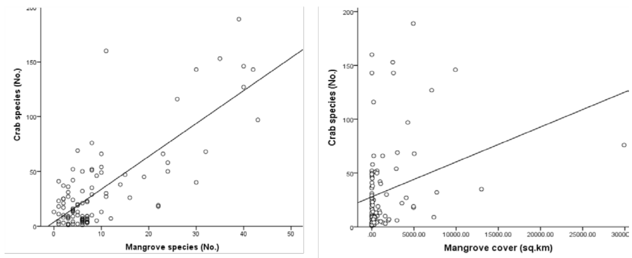

Figure 3. Relationship between mangrove crab species diversity and mangrove plant species (correlation coefficient '*r*' = 0.9; $p < 0.01$) diversity or mangrove cover ($r = 0.6$; $p < 0.01$).

The present work has brought out synonym names, which otherwise interfere with the preparation of a checklist for the exact number of crab species in mangroves of different countrises and the whole world. The mangrove crabs have a total of 818 synonyms for 318 species, and they do not have any synonyms for 71 species (Table 1). The mangrove crabs have more synonyms than brachyuran crabs in all habitats of the Earth, and the latter is represented with 1,907 synonyms for 6,793 species [17]. In other words, each mangrove crab species has 2.57 synonyms in the present work, whereas each global brachyuran species has only 0.28 synonyms, and thus the synonyms are 9.2 fold greater in mangrove crabs than all the brachyurans on the Earth. Gelasimus vocan has the highest number of 12 synonyms, found in 33 countries. This is followed by three species—Ocypode ceratophthalmus, Portunus pelagicus and Paraleptuca crassipes—which have the second largest number of 9 synonyms in 45, 35 and 27 countries respectively. This is further followed by 8 synonyms for six species—Grapsus tenuicrustatus, Pachygrapsus transverses, Portunus sanguinolentus, Tachypleus gigas, Leptograpsus variegates, and Goneplax rhomboides in 43, 40, 35, 8, 7, and 7 countries respectively (Table 1).

The occurrence and distribution of mangrove crabs vary in different sub-regions. Charybdis (Charybdis) hellerii is the only species reported to occur in all the 10 sub-regions. This is followed by six crab species, distributed in 9 sub-regions and they are Cardisoma carnifex, Grapsus albolineatus, Grapsus tenuicrustatus, Coenobita rugosus, Plagusia squamosa and Carpilius convexus. In addition, the mangrove crabs also vary in different countries. Only two crab species are reported to be present in the maximum number of 45 countries, and they are Grapsus albolineatus and Ocypode ceratophthalmus (horned ghost crab). This is followed by Thalamita crenata (mangrove swimming crab or spiny rock crab), Grapsus tenuicrustatus, Carpilius convexus (Stone crab) and Coenobita rugosus occurring in 44, 43, 43, and 41 countries respectively (Table 1). These species are active with excellent vision, air breathing or burrowing and flexible in feeding habits, and also adapted to any coastal habitats such as intertidal areas, mangrove mudflats, rocky shores, open mudflats, sandy shores and coral reefs. Hence these crab species are widely distributed among the mangrove-lined countries.

Some crab species are of restricted occurrence. As many as 55 species are confined to only one country and 90 species to a single sub-region (Table 1). These crab species deserve immediate attention for IUCN categorisation to save the species if they are endemic/endangered. It should be noted that four territories/countries do not have any record of mangrove crab species, and they are Hawaii and Tokelau located in the Pacific Islands, and St Lucia and British Virgin Island (UK) situated in North and Central America (Table 1). These territories/countries need to undertake immediate surveys and inventorization of the mangrove crabs.

The predominant family of mangrove crabs is Sesarmidae with 85 species, followed by Ocypodidae (45 spp.), Portunidae (35 spp.), macrophthalmidae (22 spp.), Camptandriidae (22 spp.), Varunidae (21 spp.), Graspidae (18 spp.), Dotillidae (18 spp.), Pilumnidae (15 spp.), Xanthidae (15 spp.) and Leucosiidae (14 spp.) (Table 1). This is in agreement with the observation that two families—Grapsidae including sub-family Sesarmidae and Ocypodidae account for over 80% of crab species diversity in the world mangroves [23].

The largest crab group in mangroves is sesarmids with a total diversity of 85 species (Table 1). The sesarmids have been recorded in Peninsular Malaysia and Singapore [11], Australia [12], Hong Kong [3], and Indo-Malaysia [1] with high species diversity of 44, 37, 26 and 25 species respectively. Hence the sesarmids attain extreme diversity in Indo-Pacific mangroves. A wide occurrence of the sesarmids in mangroves can be attributed to several reasons. The sesarmids are mostly dark brown in colour and mimic the organic-rich mangrove soil and the barks of trees, in addition to their burrow hiding and tree climbing behaviours, making them escape from predatory attacks. The sesarmids prefer shade under complex structures of mangrove vegetation for wetter and cooler conditions, and hence they colonise the mature forest with closed canopy. The sesarmids do not migrate to the open sea for spawning and larval development but are confined to mangrove/estuarine areas. The sesarmids prefer to consume cellulose-rich mangrove detritus and litter due to the presence of cellulose-digesting enzymes in their guts. In addition, they are also flexible in food consumption of different food sources, such as mud, bacteria or dead animals [16].

Table 1. Occurrence and distribution of crab species and their number of synonyms under different brachyuran crab families in different countries/sub-regions.

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synonyms	Synonyms
Sesarmidae (85 spp.)		1–7	1–28	0–6	
1	*Aratus pisonii* (H. Milne Edwards, 1837)	2	28	1	*Sesarma pisonii* H. Milne Edwards, 1837.
2	*Armases ricordi* (H. Milne Edwards, 1853)	2	19	4	*Sesarma guerini* H. Milne Edwards, 1853; *Sesarma miniata* de Saussure, 1857 ; *Sesarma ricordi* H. Milne Edwards, 1853; *Sesarma ricordi var. terrestris* Verrill, 1908.

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synony ms	Synonyms
3	*Armases magdalense* Rathbun, 1918	1	1	1	*Sesarma* (*Holometopus*) *magdalenense* Rathbun, 1918 (basionym).
4	*Armases gorei* (Abele, 1981)	2	2	1	*Sesarma gorei* Abele, 1981.
5	*Armases angustipes* (Dana, 1852)	2	2	2	*Sesarma* (*Holometopus*) *miersii iheringi* Rathbun, 1918; *Sesarma angustipes* Dana, 1852.
6	*Armases miersii* (Rathbun, 1897)	2	10	1	*Sesarma* (*Holometopus*) *miersii* Rathbun, 1897 (basionym).
7	*Armases rubripes* (Rathbun, 1897)	2	6	2	*Sesarma rubripes* Rathbun, 1897; *Sesarma trapezium* Dana, 1852.
8	*Armases elegans* (Herklots, 1851)	2	7	2	*Sesarma* (*Chiromantes*) *elegans* Herklots, 1851; *Sesarma* (*Holometopus*) *elegans* Herklots, 1851.
9	*Armases cinereum* (Bosc, 1802)	2	9	2	*Grapsus cinereus* Bosc, 1802. *Sesarma cinereum* Bosc, 1802.
10	*Sesarma curacaoense* De Man, 1892	2	11	0	-
11	*Sesarma rhizophorae* Rathbun, 1906	2	5	1	*Sesarma* (*Sesarma*) *rhizophorae* Rathbun, 1906 (basionym).
12	*Sesarma rubinofforum,* Abele, 1973	2	2	0	-
13	*Sesarma rectum* Randall, 1840	2	6	3	*Sesarma eydouxi* H. Milne Edwards, 1853; *Sesarma mulleri* A. Milne- Edwards, 1869; *Sesarma recta* Randall, 1840 (basionym).
14	*Sesarma crassipes* Cano, 1889	2	3	0	-
15	*Sesarma reticulatum* (Say, 1817)	2	5	2	*Grapsus limosus* Rafinesque, 1817; *Ocypode* (*Sesarma*) *reticulatum* Say, 1817.
16	*Guinearma kamermani* (De Man, 1883)	1	4	3	*Perisesarma kamermani* (de Man, 1883) ; *Sesarma* (*Chiromantes*) *kamermani* de Man, 1883; *Sesarma* (*Perisesarma*) *kamermani* (de Man, 1883).
17	*Guinearma alberti* (Rathbun, 1921)	1	6	3	*Perisesarma alberti* (Rathbun, 1921); *Sesarma* (*Chiromantes*) *alberti* Rathbun, 1921; (basionym) *Sesarma* (*Perisesarma*) *alberti* (Rathbun, 1921).
18	*Guinearma huzardi* (Desmarest, 1825)	2	14	4	*Grapsus huzardi* Desmarest, 1825; *Perisesarma huzardi* (Desmarest, 1825); *Sesarma* (*Perisesarma*) *huzardi* Desmarest, 1825; *Sesarma africana* H. Milne Edwards, 1837.

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synony ms	Synonyms
19	*Parasesarma guttatum* (A Milne Edwards, 1869)	4	9	3	*Chiromanthes guttatum* A. Milne Edwards, 1869; *Perisesarma guttatum* A. Milne Edwards, 1869; *Sesarma guttatum* A. Milne Edwards, 1869.
20	*Parasesarma samawati* (Gillikin & Schubart, 2004)	1	1	1	*Perisesarma samawati* Gillikin & Schubart, 2004.
21	*Parasesarma leptosoma* (Hilgendorf, 1869)	5	13	2	*Parasesarma leptosomum* Hilgendorf, 1896; *Sesarma leptosoma* Hilgendorf, 1869 (basionym).
22	*Parasesarma Plicatum* (Latreille, 1803)	5	13	2	*Cancer quadratus* Fabricius, 1798; *Ocypode plicatum* Latreille, 1803; *Sesarma plicatum* Latreille, 1803.
23	*Parasesarma pictum* (De Haan, 1835 [in De Haan, 1833–1850])	2	6	2	*Grapsus* (*Pachysoma*) *pictum* De Haan, 1835 [in De Haan, 1833–1850]; *Sesarma rupicola* Stimpson, 1858.
24	*Parasesarma bidens* (De Haan, 1835 [in De Haan, 1833–1850])	7	17	3	*Grapsus* (*Pachysoma*) *bidens* De Haan, 1835 [in De Haan, 1833–1850]; *Perisesarma bidens* (De Haan, 1835 [in De Haan, 1833–1850]) ; *Sesarma bidens* (De Haan, 1835 [in De Haan, 1833–1850]).
25	*Parasesarma eumolpe* (de Man, 1895 [in de Man, 1895–1898])	2	5	2	*Perisesarma eumolpe* (de Man, 1895 [in de Man, 1895–1898]); *Sesarma* (*Perisesarma*) *eumolpe* de Man, 1895 [in de Man, 1895–1898] (basionym).
26	*Parasesarma indiarum* (Tweedie, 1940)	5	8	3	*Perisesarma indiarum* (Tweedie, 1940); *Sesarma* (*Perisesarma*) *indica* de Man, 1902; *Sesarma bidens indiarum* Tweedie, 1940 (basionym).
27	*Parasesarma onychophorum* (de Man, 1895 [in de Man, 1895–1898])	2	6	2	*Perisesarma onychophorum* (de Man, 1895 [in de Man, 1895–1898]) ; *Sesarma* (*Perisesarma*) *onychophora* de Man, 1895 [in de Man, 1895–1898] (basionym).
28	*Parasesarma semperi* (Bürger, 1893)	2	2	2	*Perisesarma semperi* (Bürger, 1893); *Sesarma semperi* Bürger, 1893.
29	*Parasesarma batavianum* (de Man, 1890)	2	3	1	*Sesarma batavianum* de Man, 1890.
30	*Parasesarma calypso* de Man, 1895	2	5	1	*Sesarma* (*Parasesarma*) *calypso* de Man, 1895 [in de Man, 1895–1898] (basionym).
31	*Parasesarma lanchesteri* (Tweedie, 1936)	1	1	3	*Perisesarma lanchesteri* (Tweedie, 1936); *Sesarma* (*Parasesarma*) *calypso lanchesteri* Tweedie, 1936 (basionym); *Sesarma lanchesteri* Tweedie, 1936.
32	*Parasesarma melissa* (de Man, 1888 [in de Man, 1887–1888])	1	3	1	*Sesarma melissa* de Man, 1888 [in de Man, 1887–1888] (basionym).
33	*Parasesarma rutilimanum* (Tweedie, 1936)	1	1	2	*Sesarma* (*Parasesarma*) *rutilimana* Tweedie, 1936 (basionym); *Sesarma rutilimanum* Tweedie, 1936.

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synony ms	Synonyms
34	*Parasesarma darwinense* (Campbell, 1967)	4	4	2	*Perisesarma darwinense* (Campbell, 1967); *Sesarma* (*Chiromantes*) *darwinensis* Campbell, 1967.
35	*Parasesarma lenzii* (de Man, 1895 [in de Man, 1895–1898])	4	7	2	*Sesarma* (*Parasesarma*) *lenzii* de Man, 1895 [in de Man, 1895–1898] (basionym); *Sesarma lenzii* de Man, 1895 [in de Man, 1895–1898].
36	*Parasesarma messa* (Campbell, 1967)	1	1	2	*Perisesarma messa* (Campbell, 1967); *Sesarma* (*Chiromantes*) *messa* Campbell, 1967.
37	*Parasesarma erythodactylum* (Hess, 1865)	2	3	2	*Sesarma erythodactyla* Hess, 1865 (basionym); *Sesarma erythrodactylum* (Hess, 1865).
38	*Neosarmatium africanum* Ragionieri, Fratini & Schubart, 2012	1	3	0	-
39	*Neosarmatium smithi* (H. Milne Edwards, 1853)	4	11	2	*Sesarma smithi* H. Milne Edwards, 1853; *Sesarma smithii* H. Milne Edwards, 1853.
40	*Neosarmatium meinerti* (de Man, 1887)	5	20	1	*Sesarma meinerti* de Man, 1887.
41	*Neosarmatium malabaricum* (Henderson, 1893)	2	2	2	*Sarmatium indicum var. malabaricum* Henderson, 1895 (basionym); *Sarmatium malabaricum* Henderson, 1893.
42	*Neosarmatium laeve* (A. Milne Edwards, 1869)	2	2	4	*Neosarmatium aequifrons* (Rathbun, 1914); *Neosarmatium ambonensis* Serène & Moosa, 1971; *Sesarma* (*Sesarma*) *aequifrons* Rathbun, 1914; *Sesarma laeve* A. Milne Edwards, 1869.
43	*Neosarmatium trispinosum* Davie, 1994	2	4	0	-
44	*Sarmatium crassum* Dana, 1851	5	11	0	-
45	*Sarmatium striaticarpus* Davie, 1992	1	1	0	-
46	*Sarmatium germaini* (A. Milne Edwards, 1869)	3	4	1	*Sesarma germaini* A. Milne Edwards, 1869.
47	*Sarmatium germaini* (A. Milne-Edwards, 1869)	3	4	1	*Sesarma germaini* A. Milne- Edwards, 1869.
48	*Chiromantes eulimene* (de Man in Weber, 1897)	1	4	3	*Holometopus eulimene* (de Man, 1898); *Sesarma* (*Sesarma*) *eulimene* de Man, 1897; *Sesarma eulimene* de Man, 1897.
49	*Chiromantes ortmanni* (Crosnier, 1965)	1	6	5	*Holometopus ortmanni* (Crosnier, 1965); *Sesarma* (*Holometopus*) *ortmanni* Crosnier, 1965 (basionym); *Sesarma erythodactyla var. africana* Ortmann, 1894; *Sesarma erythrodactylum africanum* Ortmann, 1894; *Sesarma ortmanni* Crosnier, 1965.

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synonyms	Synonyms
50	*Sesarmops impressus* (H. Milne Edwards, 1837)	7	14	5	*Sesarma frontale* A. Milne- Edwards, 1869; *Sesarma impressum* (H. Milne Edwards, 1837); *Sesarma impressus* H. Milne Edwards, 1837; *Sesarma similis* Hess, 1865;
42	*Neosarmatium laeve* (A. Milne Edwards, 1869)	2	2	4	*Neosarmatium aequifrons* (Rathbun, 1914); *Neosarmatium ambonensis* Serène & Moosa, 1971; *Sesarma* (*Sesarma*) *aequifrons* Rathbun, 1914; *Sesarma laeve* A. Milne Edwards, 1869.
43	*Neosarmatium trispinosum* Davie, 1994	2	4	0	-
44	*Sarmatium crassum* Dana, 1851	5	11	0	-
45	*Sarmatium striaticarpus* Davie, 1992	1	1	0	-
46	*Sarmatium germaini* (A. Milne Edwards, 1869)	3	4	1	*Sesarma germaini* A. Milne Edwards, 1869.
47	*Sarmatium germaini* (A. Milne-Edwards, 1869)	3	4	1	*Sesarma germaini* A. Milne- Edwards, 1869.
48	*Chiromantes eulimene* (de Man in Weber, 1897)	1	4	3	*Holometopus eulimene* (de Man, 1898); *Sesarma* (*Sesarma*) *eulimene* de Man, 1897; *Sesarma eulimene* de Man, 1897.
49	*Chiromantes ortmanni* (Crosnier, 1965)	1	6	5	*Holometopus ortmanni* (Crosnier, 1965); *Sesarma* (*Holometopus*) *ortmanni* Crosnier, 1965 (basionym); *Sesarma erythodactyla var. africana* Ortmann, 1894; *Sesarma erythrodactylum africanum* Ortmann, 1894; *Sesarma ortmanni* Crosnier, 1965.
50	*Sesarmops impressus* (H. Milne Edwards, 1837)	7	14	5	*Sesarma frontale* A. Milne- Edwards, 1869; *Sesarma impressum* (H. Milne Edwards, 1837); *Sesarma impressus* H. Milne Edwards, 1837; *Sesarma similis* Hess, 1865;
42	*Neosarmatium laeve* (A. Milne Edwards, 1869)	2	2	4	*Neosarmatium aequifrons* (Rathbun, 1914); *Neosarmatium ambonensis* Serène & Moosa, 1971; *Sesarma* (*Sesarma*) *aequifrons* Rathbun, 1914; *Sesarma laeve* A. Milne Edwards, 1869.
43	*Neosarmatium trispinosum* Davie, 1994	2	4	0	-
44	*Sarmatium crassum* Dana, 1851	5	11	0	-
45	*Sarmatium striaticarpus* Davie, 1992	1	1	0	-
46	*Sarmatium germaini* (A. Milne Edwards, 1869)	3	4	1	*Sesarma germaini* A. Milne Edwards, 1869.

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synony ms	Synonyms
47	*Sarmatium germaini* (A. Milne-Edwards, 1869)	3	4	1	*Sesarma germaini* A. Milne- Edwards, 1869.
48	*Chiromantes eulimene* (de Man in Weber, 1897)	1	4	3	*Holometopus eulimene* (de Man, 1898); *Sesarma* (*Sesarma*) *eulimene* de Man, 1897; *Sesarma eulimene* de Man, 1897.
49	*Chiromantes ortmanni* (Crosnier, 1965)	1	6	5	*Holometopus ortmanni* (Crosnier, 1965); *Sesarma* (*Holometopus*) *ortmanni* Crosnier, 1965 (basionym); *Sesarma erythodactyla var. africana* Ortmann, 1894; *Sesarma erythro-dactylum africanum* Ortmann, 1894; *Sesarma ortmanni* Crosnier, 1965.
50	*Sesarmops impressus* (H. Milne Edwards, 1837)	7	14	5	*Sesarma frontale* A. Milne- Edwards, 1869; *Sesarma impressum* (H. Milne Edwards, 1837); *Sesarma impressus* H. Milne Edwards, 1837; *Sesarma similis* Hess, 1865; *Sesarmops impressum* (H. Milne Edwards, 1837).
51	*Sesarmops intermedius* (De Haan, 1835 [in De Haan, 1833–1850])	2	4	1	*Grapsus* (*Pachysoma*) *intermedius* De Haan, 1835[in De Haan, 1833–1850].
52	*Sesarmoides longipes* (Krauss, 1843)	2	3	1	*Grapsus* (*Sesarma*) *longipes* Krauss, 1843 (basionym).
53	*Sesarmoides kraussi* (de Man, 1888 [in de Man, 1887–1888])	4	7	1	*Sesarma Kraussi* de Man, 1888 [in de Man, 1887–1888] (basionym).
54	*Sesarmoides borneensis* (Tweedie, 1950)	2	3	1	*Sesarma Kraussi borneensis* Tweedie, 1950 (basionym).
55	*Clistocoeloma villosum* (A. Milne-Edwards, 1869)	4	10	1	*Sesarma villosum* A. Milne Edwards, 1869.
56	*Clistocoeloma merguiense* de Man, 1888 [in de Man, 1887–1888]	5	10	1	*Clistocoeloma Merguiensis* de Man, 1888 [in de Man, 1887–1888] (basionym).
57	*Clistocoeloma lanatum* (Alcock, 1900)	3	3	1	*Sesarma lanatum* Alcock, 1900.
58	*Clistocoeloma suvaense* Edmondson, 1951	1	1	0	-
59	*Selatium brockii* (de Man, 1887)	5	9	3	*Selatium brocki* (de Man, 1887); *Sesarma brocki* de Man, 1887; *Sesarma brockii* de Man, 1887.
60	*Selatium elongatum* (A. Milne Edwards, 1869)	4	7	2	*Sesarma elongatum* A. Milne Edwards, 1869; *Sesarma latifemur* Alcock, 1900.
61	*Episesarma mederi* (H. Milne Edwards, 1853)	3	8	3	*Sesarma mederi* A. Milne Edwards, 1853(basionym); *Sesarma taeniolata* Miers, 1877; *Sesarma taeniolata* White, 1847.
62	*Episesarma versicolor* (Tweedie, 1940)	2	6	1	*Sesarma versicolor* Tweedie, 1940 (basionym).
63	*Episesarma chentongense* (Serène & Soh, 1967)	1	1	1	*Sesarma* (*Sesarma*) *chentongense* Serène & Soh, 1967.

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synonyms	Synonyms
64	*Episesarma palawanense* (Rathbun, 1914)	1	2	1	*Sesarma* (*Sesarma*) *palawanense* Rathbun, 1914 (basionym).
65	*Episesarma singaporense* (Tweedie, 1936)	1	2	1	*Sesarma* (*Sesarma*) *singaporensis* Tweedie, 1936 (basionym).
66	*Episesarma lafondii* (Hombron & Jacquinot, 1846)	2	5	1	*Sesarma lafondii* Hombron & Jacquinot, 1846.
67	*Muradium tetragonum* (Fabricius, 1798)	1	1	2	*Cancer fascicularis* Herbst, 1799; *Cancer tetragonum* Fabricius, 1798.
68	*Labuanium rotundatum* (Hess, 1865)	3	9	6	*Sarmatium faxoni* Rathbun, 1906; *Sesarma* (*Episesarma*) *rotundata* (Hess, 1865); *Sesarma dentifrons* A. Milne Edwards, 1869; *Sesarma gardineri* Borradaile, 1900; *Sesarma oceanica* de Man, 1889; *Sesarma rotundatum* Hess, 1865 (basionym).
69	*Labuanium politum* (de Man, 1888 [in de Man, 1887–1888])	1	3	1	*Sesarma polita* de Man, 1888 [in de Man, 1887–1888] (basionym).
70	*Metasesarma obesum* (Dana, 1851)	7	27	6	*Holometopus obesus* (Dana, 1851); *Metasesarma granularis* Heller, 1862; *Metasesarma rousseauxi* H. Milne Edwards, 1853; *Metasesarma rugulosa* Heller, 1865; *Sesarma obesum* Dana, 1851; *Sesarma rousseauxi.*
71	*Nanosesarma andersoni* (de Man, 1888 [in de Man, 1887–1888])	4	7	1	*Sesarma andersoni* de Man, 1888 [in de Man, 1887–1888] (basionym).
72	*Nanosesarma batavicum* (Moreira, 1903)	2	5	1	*Sesarma batavica* Moreira, 1903 (basionym).
73	*Nanosesarma minutum* (de Man, 1887)	5	11	4	*Nanosesarma gordoni* De Man, 1887; *Sesarma* (*Sesarma*) *gordoni* Shen, 1935; *Sesarma barbimanum* Cano, 1889; *Sesarma minutum* de Man, 1887.
74	*Nanosesarma edamense* (de Man, 1887)	1	1	1	*Sesarma edamensis* de Man, 1887.
65	*Episesarma singaporense* (Tweedie, 1936)	1	2	1	*Sesarma* (*Sesarma*) *singaporensis* Tweedie, 1936 (basionym).
66	*Episesarma lafondii* (Hombron & Jacquinot, 1846)	2	5	1	*Sesarma lafondii* Hombron & Jacquinot, 1846.
67	*Muradium tetragonum* (Fabricius, 1798)	1	1	2	*Cancer fascicularis* Herbst, 1799; *Cancer tetragonum* Fabricius, 1798.

Table 1 continued

No.	**Name of Crab Species**	**No. of Sub-regions**	**No. of Countries**	**No. of Synonyms**	**Synonyms**
68	*Labuanium rotundatum* (Hess, 1865)	3	9	6	*Sarmatium faxoni* Rathbun, 1906; *Sesarma* (*Episesarma*) *rotundata* (Hess, 1865); *Sesarma dentifrons* A. Milne Edwards, 1869; *Sesarma gardineri* Borradaile, 1900; *Sesarma oceanica* de Man, 1889; *Sesarma rotundatum* Hess, 1865 (basionym).
69	*Labuanium politum* (de Man, 1888 [in de Man, 1887–1888])	1	3	1	*Sesarma polita* de Man, 1888 [in de Man, 1887–1888] (basionym).
70	*Metasesarma obesum* (Dana, 1851)	7	27	6	*Holometopus obesus* (Dana, 1851); *Metasesarma granularis* Heller, 1862; *Metasesarma rousseauxi* H. Milne Edwards, 1853; *Metasesarma rugulosa* Heller, 1865; *Sesarma obesum* Dana, 1851; *Sesarma rousseauxi.*
71	*Nanosesarma andersoni* (de Man, 1888 [in de Man, 1887–1888])	4	7	1	*Sesarma andersoni* de Man, 1888 [in de Man, 1887–1888] (basionym).
72	*Nanosesarma batavicum* (Moreira, 1903)	2	5	1	*Sesarma batavica* Moreira, 1903 (basionym).
73	*Nanosesarma minutum* (de Man, 1887)	5	11	4	*Nanosesarma gordoni* De Man, 1887; *Sesarma* (*Sesarma*) *gordoni* Shen, 1935; *Sesarma barbimanum* Cano, 1889; *Sesarma minutum* de Man, 1887.
74	*Nanosesarma edamense* (de Man, 1887)	1	1	1	*Sesarma edamensis* de Man, 1887.
75	*Nanosesarma nunongi* Tweedie, 1951	2	2	0	-
76	*Nanosesarma pontianacense* (de Man, 1895 [in de Man, 1895–1898])	1	2	1	*Sesarma* (*Episesarma*) *pontianacensis* de Man, 1895 [in de Man, 1895–1898] (basionym).
77	*Fasciarma fasciatum* (Lanchester, 1900)	2	5	3	*Perisesarma fasciatum* (Lanchester, 1900); *Sesarma* (*Chiromantes*) *siamense* Rathbun, 1909; *Sesarma fasciatum* Lanchester, 1900 (basionym).
78	*Pseudosesarma edwardsi* (de Man, 1888 [in de Man, 1887–1888])	5	11	3	*Sesarma* (*Sesarma*) *edwardsi* (de Man, 1888 [in de Man, 1887–1888]); *Sesarma edwardsi* de Man, 1888 [in de Man, 1887–1888] (basionym); *Sesarma edwardsii* de Man, 1888 [in de Man, 1887–1888].
79	*Pseudosesarma bocourti* (A. Milne Edwards, 1869)	2	4	2	*Sesarma bocourti* A. Milne Edwards, 1869; *Sesarma cheiragona* Targioni Tozzetti, 1877.
80	*Pseudosesarma crassimanum* (De Man, 1888)	2	3	1	*Sesarma crassimanum* De Man, 1888.

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synonyms	Synonyms
81	*Perisesarma dusumieri* (H. Milne Edwards, 1853)	1	3	1	*Sesarma dussumieri* H. Milne Edwards, 1853.
82	*Perisesarma tuerkayi* Shahdadi, Davie & Schubart, 2017	1	1	0	-
83	*Tiomanium indicum* (H. Milne Edwards, 1837)	3	4	2	*Sesarma* (*Sesarma*) *tiomanense* Rathbun, 1913; *Sesarma indicum* H. Milne Edwards, 1837.
84	*Neosesarma gemmiferum* (Tweedie, 1936)	1	1	1	*Sesarma gemmiferum* Tweedie, 1936.
85	*Haberma tingkok* Cannicci & P.K.L. Ng, 2017	1	1	0	-
Ocypodidae (45 spp.)		1–8	1–45	0–12	
86	*Leptuca leptodactyla* (Rathbun, in Rankin, 1898)	2	11	3	*Uca* (*Leptuca*) *leptodactyla* Rathbun in Rankin, 1898; *Uca leptodactyla* Rathbun in Rankin, 1898 (basionym); *Uca leptostyla* Nutting, 1919.
87	*Minuca rapax* (Smith, 1870)	3	20	4	*Gelasimus palustris* H. Milne Edwards, 1852; *Gelasimus rapax* Smith, 1870 (basionym); *Uca* (*Minuca*) *rapax* (Smith, 1870); *Uca pugnax brasiliensis* de Oliveira, 1939.
88	*Leptuca thayeri* (Rathbun, 1900)	2	15	3	*Minuca thayeri* (Rathbun, 1900); *Uca* (*Minuca*) *thayeri* Rathbun, 1900; *Uca thayeri* Rathbun, 1900.
89	*Minuca vocator* (Herbst, 1804)	2	18	5	*Cancer vocator* Herbst, 1804; *Uca* (*Minuca*) *vocator* (Herbst, 1804); *Uca lanigera* von Hagen, 1968; *Uca murifecenta* Crane, 1943; *Uca salsisitus* de Oliveira, 1939.
90	*Ucides cordatus* (Linnaeus, 1763)	2	17	4	*Cancer cordatus* Linnaeus, 1763; *Cancer uca* Linnaeus, 1767; *Ocypode fossor* Latreille, 1802; *Uca pilosipes* Gill, 1859.
91	*Uca maracoani* (Latreille, 1802)	2	10	2	*Ocypode maracoani* Latreille, 1802; *Uca* (*Uca*) *maracoani* (Latreille, 1802).
92	*Leptuca cumulanta* (Crane, 1943)	2	7	1	*Uca* (*Leptuca*) *cumulanta* Crane, 1943.
93	*Minuca victoriana* (von Hagen, 1987)	1	1	1	*Uca* (*Minuca*) *victoriana* von Hagen, 1987.
94	*Minuca mordax* (Smith, 1870)	3	14	2	*Gelasimus mordax* Smith, 1870 (basionym); *Uca* (*Minuca*) *mordax* (Smith, 1870).
95	*Leptuca uruguayensis* (Nobili, 1901)	1	1	2	*Uca* (*Leptuca*) *uruguayensis* Nobili, 1901; *Uca olympioi* de Oliveira, 1939.
96	*Minuca burgersi* (Holthuis, 1967)	3	24	4	*Gelasimus affinis* Streets, 1872; *Uca* (*Minuca*) *burgersi* Holthuis, 1967; *Uca burgersi* Holthuis, 1967 (basionym); *Uca panema* Coelho, 1972.

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synony ms	Synonyms
97	*Paraleptuca chlorophthal-mus* Milne Edwards, 1837)	4	13	4	*Gelasimus chlorophthalmus* H. Milne Edwards, 1837; *Uca* (*Paraleptuca*) *chlorophthalmus* (H. Milne Edwards, 1837); *Uca* (*Paraleptuca*) *chlorophthalmus chloroph-thalmus* (H. Milne Edwards, 1837); *Uca amazonensis* Doflein, 1899.
98	*Cranuca inversa* (Hoffmann, 1874)	3	12	4	*Gelasimus inversus* Hoffmann, 1874 (basio-nym); *Gelasimus smithii* Kingsley, 1880; *Uca* (*Cranuca*) *inversa* (Hoffmann, 1874); *Uca* (*Cranuca*) *inversa* (Hoffmann, 1874).
99	*Austruca annulipes* (H. Milne Edwards, 1837)	7	30	5	*Gelasimus annulipes* H. Milne Edwards, 1837 (basionym); *Gelasimus porcellanus* White, 1847; *Uca* (*Austruca*) *annulipes* (H. Milne Edwards, 1837); *Uca* (*Paraleptuca*) *annulipes* (H. Milne Edwards, 1837); *Uca consobrinus* Verwey, 1930.
100	*Gelasimus tetragonon* (Herbst, 1790)	7	32	7	*Cancer tetragonon* Herbst, 1790; *Gelasimus af-finis* Guérin, 1829; *Gelasimus duperreyi* Guérin, 1829; *Gelasimus variatus* Hess, 1865 ; *Uca* (*Gelasimus*) *tetragonon* (Herbst, 1790); *Uca affinis* Guérin, 1829; *Uca duperreyi* Guérin, 1829.
101	*Tubuca urvillei* (H. Milne Edwards, 1852)	5	12	2	*Gelasimus urvillei* H. Milne Edwards, 1852; *Uca* (*Tubuca*) *urvillei* (H. Milne Edwards, 1852).
102	*Gelasimus vocans* (Lin-naeus, 1758)	8	33	12	*Cancer vocans* Linnaeus, 1758; *Gelasimus cul-trimanus* White, 1847; *Gelasimus marionis* Desmarest, 1823; *Gelasimus nitidus* Dana, 1851; *Uca* (*Gelasimus*) *vocans* (Linnaeus, 1758); *Uca* (*Gelasimus*) *vocans excisa* (Nobili, 1906); *Uca* (*Gelasimus*) *vocans* (Linnaeus, 1758); *Uca* (*Thalassuca*) *vocans* *Uca marionis* (Desmarest, 1823); *Uca marionis cultrimana* (White, 1847); *Uca marionis excisa* Nobili, 1906; *Uca marionis f. excisa* Nobili, 1906.
103	*Ocypode ceratophthalmus* (Pallas, 1772)	8	45	9	*Cancer arenarius* Toreen in Osbeck, 1765; *Cancer caninus* Herbst, 1782; *Cancer ceratoph-thalmus* Pallas, 1772; *Cancer francisci* Curtiss, 1938; *Ocipode urvillii* Guérin, 1829; *Ocypoda Macleayana* Hess, 1865; *Ocypode brevicornis var. longicornuta* Dana, 1852; *Ocypode longicornuta* Dana, 1852; *Ocypode urvillei* Guérin, 1838.

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synony ms	Synonyms
104	*Ocypode saratan* (Forskål, 1775)	2	10	3	*Cancer saratan* Forskål, 1775; *Ocypode aegyptiaca* Gerstaecker, 1856; *Ocypode aegyptica* Gerstaecker, 1856.
105	*Austruca perplexa* (H. Milne Edwards, 1852)	6	15	5	*Gelasimus annulipes var. albimana* H. Milne Edwards, 1852; *Gelasimus perplexa* H. Milne Edwards, 1837; *Uca* (*Austruca*) *annulipes var. orientalis* Nobili, 1901; *Uca* (*Austruca*) *perplexa* (H. Milne Edwards, 1837); *Uca* (*Paraleptuca*) *perplexa* (H. Milne Edwards, 1837).
106	*Austruca iranica* (Pretzmann, 1971)	2	5	1	*Uca* (*Austruca*) *iranica* Pretzmann, 1971.
107	*Austruca sindensis* (Alcock, 1900)	2	3	3	*Gelasimus sindensis* Alcock, 1900; *Uca* (*Austruca*) *sindensis* (Alcock, 1900); *Uca* (*Paraleptuca*) *sindensis* (Alcock, 1900).
108	*Austruca lactea* (De Haan, 1835 [in De Haan, 1833–1850])	6	17	6	*Gelasimus forceps* H. Milne Edwards, 1837; *Ocypode* (*Gelasimus*) *lactea* De Haan, 1835 [in De Haan, 1833–1850]; *Uca* (*Austruca*) *lactea* (De Haan, 1835 [in De Haan, 1833–1850]); *Uca* (*Paraleptuca*) *lactea* (De Haan, 1835 [in De Haan, 1833–1850]); *Uca* (*Paraleptuca*) *lactea annulipes* (H. Milne Edwards, 1837); *Uca orientalis* Nobili, 1901.
109	*Austruca triangularis* (A. Milne Edwards, 1873)	6	16	4	*Gelasimus triangularis* A. Milne Edwards, 1873 (basionym); *Gelasimus triangularis var. variabilis* de Man, 1891; *Uca* (*Austruca*) *triangularis* (A. Milne-Edwards, 1873); *Uca* (*Paraleptuca*) *triangularis* (A. Milne-Edwards, 1873).
110	*Leptuca pugilator* (Bosc, 1802)	2	3	3	*Ocypoda pugilator* Bosc, 1801; *Ocypode citharoedicus* Say, 1817 ; *Uca* (*Leptuca*) *pugilator* (Bosc, 1801).
111	*Ocypode cordimana* Latreille, 1818	7	36	1	*Cancer roberti* Curtiss, 1938.
112	*Ocypode macrocera* H. Milne Edwards, 1852	4	6	1	*Ocypoda portonovoensis* Prem Kumar, 1964 (junior synonym).
113	*Ocypode platytarsis* H. Milne Edwards, 1852	2	3	0	-
114	*Tubuca acuta* (Stimpson, 1858)	2	4	2	*Gelasimus acutus* Stimpson, 1858 (basionym); *Uca* (*Tubuca*) *acuta* (Stimpson, 1858).
115	*Tubuca dussumieri* (H. Milne Edwards, 1852)	6	16	5	*Gelasimus caerulens* Adams, in Belcher, 1848; *Gelasimus dubius* Stimpson, 1858 ; *Gelasimus dussumieri* H. Milne Edwards, 1852; *Uca* (*Deltuca*) *dussumieri* *Uca* (*Tubuca*) *dussumieri* (H. Milne Edwards, 1852).

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synonyms	Synonyms
116	*Tubuca rosea* (Tweedie, 1937)	2	7	2	*Gelasimus roseus* Tweedie, 1937 (basionym); *Uca* (*Tubuca*) *rosea* (Tweedie, 1937).
117	*Uca* (*Paraleptuca*) *bengali* Crane, 1975	2	3	2	*Uca bengali* Crane, 1975; *Ausrruca bengali* Crane, 1975.
118	*Tubuca coarctata* (H. Milne Edwards, 1852)	5	10	6	*Gelasimus coarctata* H. Milne Edwards, 1852; *Gelasimus thomsoni* Kirk, 1881; *Uca* (*Tubuca*) *coarctata* (H. Milne Edwards, 1852); *Uca ischnodactylus* Nemec, 1939; *Uca mearnsi* Rathbun, 1913; *Uca rathbunae* Pearse, 1912.
119	*Tubuca paradussumieri* (Bott, 1973)	3	9	2	*Uca* (*Deltuca*) *dussumieri spinata* Crane, 1975; *Uca* (*Tubuca*) *paradussumieri* Bott, 1973.
120	*Tubuca forcipata* (Adams & White, 1849)	3	8	4	*Gelasimus forcipatus* Adams & White, 1849; *Uca* (*Tubuca*) *forcipata* (Adams & White, 1849); *Uca manii* Rathbun, 1909 ; *Uca rubripes* Estampador, 1937.
121	*Tubuca rhizophorae* (Tweedie, 1950)	1	2	2	*Uca* (*Tubuca*) *rhizophorae* Tweedie, 1950; *Uca rhizophorae* Tweedie, 1950 (basionym).
122	*Tubuca bellator* (White, 1847)	3	5	5	*Gelasimus bellator* White, 1847; *Gelasimus signatus var. angustifrons* de Man, 1891; *Uca* (*Australuca*) *bellator* (White, 1847); *Uca bellator* (White, 1847); *Uca brevifrons var. delicata* Maccagno, 1928.
123	*Gelasimus jocelynae* (Shih, Naruse & P.K.L. Ng, 2010)	3	8	1	*Uca* (*Gelasimus*) *jocelynae* Shih, Naruse & P.K.L. Ng, 2010 (basionym).
124	*Paraleptuca crassipes* (White, 1847)	6	27	9	*Gelasimus crassipes* White, 1847; *Gelasimus gaimardi* H. Milne Edwards, 1852; *Gelasimus latreillei* H. Milne Edwards, 1852; *Gelasimus pulchellus* Stimpson, 1858; *Uca* (*Paraleptuca*) *chlorophthalmus crassipes* Adams & White, 1848; *Uca* (*Paraleptuca*) *crassipes* (White, 1847); *Uca gaimardi* (H. Milne Edwards, 1852); *Uca latreillei* (H. Milne Edwards, 1852); *Uca novaeguineae* Rathbun, 1913.
125	*Tubuca seismella* (Crane, 1975)	2	2	1	*Uca* (*Australuca*) *seismella* Crane, 1975.
126	*Tubuca flammula* (Crane, 1975)	2	2	1	*Uca* (*Tubuca*) *flammula* Crane, 1975.
127	*Tubuca signata* (Hess, 1865)	2	3	4	*Gelasimus signata* Hess, 1865; *Gelasimus signatus* Hess, 1865 (basionym); *Uca* (*Australuca*) *bellator minima* Crane, 1975; *Uca* (*Australuca*) *signata* (Hess, 1865).
128	*Tubuca longidigitum* (Kingsley, 1880)	1	1	2	*Gelasimus longidigitum* Kingsley, 1880; *Uca longidigitum* (Kingsley, 1880).

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synony ms	Synonyms
129	*Gelasimus vomeris* (McNeill, 1920)	4	10	2	*Uca* (*Gelasimus*) *vomeris* McNeill, 1920; *Uca marionis var. vomeris* McNeill, 1920 (basionym).
130	*Tubuca polita* (Crane, 1975)	2	2	1	*Uca* (*Australuca*) *polita* Crane, 1975.
Gecarcinidae (6 spp.)		1–9	1–42	1–6	
131	*Cardisoma guanhumi* Latreille in Latreille, Le Peletier, Serville & Guérin, 1828	5	33	4	*Cancer guanhumi* Berthold, 1827; *Cardisoma diurnum* Gill, 1862; *Cardisoma quadrata* de Saussure, 1857; *Ocypoda gigantea* de Fréminville, 1835.
132	*Cardisoma carnifex* (Herbst, 1796)	9	42	6	*Cancer carnifex* Herbst, 1796; *Cancer tahiticus* Curtiss, 1938; *Cancer urvillei* H. Milne Edwards, 1853; *Cardisoma aspasia* Adams in Belcher, 1848; *Cardisoma obesum* Dana, 1851; *Perigrapsus excelsus* Heller, 1862 (junior synonym).
133	*Barytelphusa cunicularis* (Westwood, 1836)	1	1	1	*Thelphusa cunicularis* Westwood, 1836.
134	*Cylindrotelphusa steniops* (Alcock, 1909)	1	1	1	*Gecarcinucus steniops* Alcock, 1909.
135	*Sartoriana spinigera* (Wood Mason, 1871)	1	4	4	*Paratelphusa spinigera* Wood Mason, 1871; *Parathelphusa spinigera* Wood Mason, 1871; *Telphusa spinigera* Wood Mason, 1871; *Thelphusa spinigera* White, 1847.
136	*Spiralothelphusa hydrodroma* (Herbst, 1794)	1	2	1	*Cancer hydrodroma* Herbst, 1794.
Grapsidae (18 spp.)		1–9	1–45	0–8	
137	*Goniopsis cruentata* (Latreille, 1803)	3	33	2	*Grapsus* (*Goniopsis*) *cruentata* Latreille, 1803; *Grapsus longipes* Randall, 1840;
138	*Pachygrapsus gracilis* (Saussure, 1857)	2	5	2	*Grapsus guadulpensis* Desbonne in Desbonne & Schramm, 1867; *Metopograpsus gracilis* de Saussure, 1857(basionym).
139	*Pachygrapsus transverses* (Gibbes, 1850)	8	40	8	*Goniograpsus innotatus* Dana, 1851; *Grapsus declivifrons* Heller, 1862; *Grapsus transversus* Gibbes, 1850 (basionym); *Leptograpsus rugulosus* H. Milne Edwards, 1853; *Metopograpsus dubius* Saussure, 1858; *Metopograpsus miniatus* de Saussure, 1857; *Pachygrapsus advena* Catta, 1876; *Pachygrapsus intermedius* Heller, 1862.
140	*Goniopsis pulchra* (Lockington, 1877)	2	8	1	*Goniograpsus pulchra* Lockington, 1877.

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synonyms	Synonyms
141	*Goniopsis pelii* (Herklots, 1851)	1	14	2	*Grapsus* (*Grapsus*) *pelii* Herklots, 1851; *Grapsus* (*Grapsus*) *simplex* Herklots, 1851.
142	*Grapsus fourmanoiri* Crosnier, 1965	1	8	0	-
143	*Metopograpsus messor* (Forskål, 1775)	8	36	4	*Cancer messor* Forskål, 1775; *Eurycarcinus messor* (Forskål, 1775); *Grapsus* (*Pachygrapsus*) *aethiopicus* Hilgendorf, 1869; *Grapsus gaimardi* Audouin, 1826.
144	*Metopograpsus oceanicus* (Hombron & Jacquinot, 1846 [in Hombron & Jacquinot, 1842–1854])	6	14	3	*Eurycarcinus oceanicus* (Hombron & Jacquinot, 1846) ; *Grapsus* (*Grapsus*) *sulcifer* Herklots, 1861; *Grapsus oceanicus* Hombron & Jacquinot, 1846 [in Hombron & Jacquinot, 1842–1854] (basionym).
145	*Metopograpsus thukuhar* (Owen, 1839)	8	36	4	*Grapsus thukuhar* Owen, 1839 (basionym); *Metopograpsus eydouxi* H. Milne Edwards, 1853; *Metopograpsus intermedius* H. Milne Edwards, 1853; *Pachygrapsus parallelus* Randall, 1840.
146	*Grapsus albolineatus* Latreille in Milbert, 1812	9	45	6	*Cancer strigosus* Herbst, 1799; *Grapsus* (*Goniopsis*) *flavipes* MacLeay, 1838; *Grapsus albolineatus* Lamarck, 1818; *Grapsus longipes* Stimpson, 1858; *Grapsus peroni* H. Milne Edwards, 1853; *Grapsus strigosus* Herbst, 1799.
147	*Grapsus intermedius* de Man, 1888	4	8	0	-
148	*Grapsus tenuicrustatus* (Herbst, 1783)	9	43	8	*Cancer ballantei* Curtiss, 1938; *Cancer tenuicrustatus* Herbst, 1783; *Grapsus gracilipes* H. Milne Edwards, 1853; *Grapsus gracillimus* Sendler, 1923; *Grapsus hirtus* Randall, 1840; *Grapsus pharaonis* H. Milne Edwards, 1853; *Grapsus rude* H. Milne Edwards, 1837; *Grapsus rudis* H. Milne Edwards, 1853.
149	*Metopograpsus frontalis* Miers, 1880	5	10	2	*Metopograpsus messor gracilipes* de Man, 1891; *Metopograpsus messor var. frontalis* Miers, 1880 (basionym).
150	*Metopograpsus latifrons* (White, 1847)	6	18	5	*Grapsus* (*Grapsus*) *dilatatus* De Haan in Herklots, 1861; *Grapsus* (*Grapsus*) *dilatatus* de Man, 1879; *Grapsus latifrons* White, 1847; *Metopograpsus maculatus* H. Milne Edwards, 1853; *Metopograpsus pictus* A. Milne-Edwards, 1867.
151	*Pachygrapsus propinquus* de Man, 1908	1	1	0	-
152	*Metopograpsus quadridentatus* Stimpson, 1858	4	9	2	*Grapsus* (*Grapsus*) *plicatus* Herklots, 1861; *Pachygrapsus quadratus* Tweedie, 1936.

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synonyms	Synonyms
153	*Helice formosensis* Rathbun, 1931	1	2	1	*Helice tridens formosensis* Rathbun, 1931 (basionym).
154	*Leptograpsus variegatus* (Fabricius, 1793)	6	7	8	*Cancer variegatus* Fabricius, 1793; *Grapsus personatus* Lamarck, 1818; *Grapsus planifrons* Dana, 1851; *Grapsus strigilatus* White, 1842; *Leptograpsus ansoni* H. Milne Edwards, 1853; *Leptograpsus gayi* H. Milne Edwards, 1853; *Leptograpsus verreauxi* H. Milne Edwards, 1853; *Sesarma pentagona* Hutton, 1875.
Panopeidae (4 spp.)		2–4	7–26	1–4	
155	*Eurytium limosum* (Say, 1818)	2	16	1	*Cancer limosa* Say, 1818.
156	*Panopeus herbstii* H. Milne Edwards, 1834	4	26	4	*Eupanopeus herbstii* H. Milne Edwards, 1834; *Eupanopeus herbstii herbstii* H. Milne
149	*Metopograpsus frontalis* Miers, 1880	5	10	2	*Metopograpsus messor gracilipes* de Man, 1891; *Metopograpsus messor var. frontalis* Miers, 1880 (basionym).
150	*Metopograpsus latifrons* (White, 1847)	6	18	5	*Grapsus* (*Grapsus*) *dilatatus* De Haan in Herklots, 1861; *Grapsus* (*Grapsus*) *dilatatus* de Man, 1879; *Grapsus latifrons* White, 1847; *Metopograpsus maculatus* H. Milne Edwards, 1853; *Metopograpsus pictus* A. Milne-Edwards, 1867.
151	*Pachygrapsus propinquus* de Man, 1908	1	1	0	-
152	*Metopograpsus quadridentatus* Stimpson, 1858	4	9	2	*Grapsus* (*Grapsus*) *plicatus* Herklots, 1861; *Pachygrapsus quadratus* Tweedie, 1936.
153	*Helice formosensis* Rathbun, 1931	1	2	1	*Helice tridens formosensis* Rathbun, 1931 (basionym).
154	*Leptograpsus variegatus* (Fabricius, 1793)	6	7	8	*Cancer variegatus* Fabricius, 1793; *Grapsus personatus* Lamarck, 1818; *Grapsus planifrons* Dana, 1851; *Grapsus strigilatus* White, 1842; *Leptograpsus ansoni* H. Milne Edwards, 1853; *Leptograpsus gayi* H. Milne Edwards, 1853; *Leptograpsus verreauxi* H. Milne Edwards, 1853; *Sesarma pentagona* Hutton, 1875.
Panopeidae (4 spp.)		2–4	7–26	1–4	
155	*Eurytium limosum* (Say, 1818)	2	16	1	*Cancer limosa* Say, 1818.
156	*Panopeus herbstii* H. Milne Edwards, 1834	4	26	4	*Eupanopeus herbstii* H. Milne Edwards, 1834; *Eupanopeus herbstii herbstii* H. Milne

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synonyms	Synonyms
149	*Metopograpsus frontalis* Miers, 1880	5	10	2	*Metopograpsus messor gracilipes* de Man, 1891; *Metopograpsus messor var. frontalis* Miers, 1880 (basionym).
150	*Metopograpsus latifrons* (White, 1847)	6	18	5	*Grapsus* (*Grapsus*) *dilatatus* De Haan in Herklots, 1861; *Grapsus* (*Grapsus*) *dilatatus* de Man, 1879; *Grapsus latifrons* White, 1847; *Metopograpsus maculatus* H. Milne Edwards, 1853; *Metopograpsus pictus* A. Milne-Edwards, 1867.
151	*Pachygrapsus propinquus* de Man, 1908	1	1	0	-
152	*Metopograpsus quadridentatus* Stimpson, 1858	4	9	2	*Grapsus* (*Grapsus*) *plicatus* Herklots, 1861; *Pachygrapsus quadratus* Tweedie, 1936.
153	*Helice formosensis* Rathbun, 1931	1	2	1	*Helice tridens formosensis* Rathbun, 1931 (basionym).
154	*Leptograpsus variegatus* (Fabricius, 1793)	6	7	8	*Cancer variegatus* Fabricius, 1793; *Grapsus personatus* Lamarck, 1818; *Grapsus planifrons* Dana, 1851; *Grapsus strigilatus* White, 1842; *Leptograpsus ansoni* H. Milne Edwards, 1853; *Leptograpsus gayi* H. Milne Edwards, 1853; *Leptograpsus verreauxi* H. Milne Edwards, 1853; *Sesarma pentagona* Hutton, 1875.
Panopeidae (4 spp.)		2–4	7–26	1–4	
155	*Eurytium limosum* (Say, 1818)	2	16	1	*Cancer limosa* Say, 1818.
156	*Panopeus herbstii* H. Milne Edwards, 1834	4	26	4	*Eupanopeus herbstii* H. Milne Edwards, 1834; *Eupanopeus herbstii herbstii* H. Milne Edwards, 1834; *Galene hawaiensis* Dana, 1852; *Panopeus herbstii f. typica* Rathbun, 1930.
157	*Panopeus americanus* de Saussure, 1857	2	7	1	*Panopeus areolatus* Benedict & Rathbun, 1891.
158	*Rhithropanopeus harrisii* (Gould, 1841)	4	9	3	*Panopeus wurdemannii* Gibbes, 1850; *Pilumnus harrisii* Gould, 1841; *Pilumnus tridentatus* Maitland, 1874.
Portunidae (35 spp.)		2–10	2–44	0–9	
159	*Callinectes exasperatus* (Gerstaecker, 1856)	2	16	3	*Callinectes tumidus* Ordway, 1863; *Lupa trispinosa* Leach, 1816; *Lupea exasperatus* Gerstaecker, 1856.
160	*Scylla serrata* (Forskål, 1775)	8	37	4	*Achelous crassimanus* MacLeay, 1838; *Cancer serrata* Forskål, 1775; *Lupa lobifrons* H. Milne Edwards, 1834; *Scylla tranquebarica var. oceanica* Dana, 1852.

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synony ms	Synonyms
161	*Thalamita crenata* Rüppell, 1830	8	44	3	*Talamita crenata* Rüppell, 1830 (basionym); *Thalamita kotoensis* Tien, 1969; *Thalamita prymna var. crenata* Rüppell, 1830.
162	*Charybdis* (*Charybdis*) *affinis* Dana, 1852	4	8	1	*Charybdis barneyi* Gordon, 1930.
163	*Charybdis* (*Charybdis*) *annulata* (Fabricius, 1798)	7	18	2	*Portunus annulata* Fabricius, 1798; *Portunus annulatus* Weber, 1795.
164	*Charybdis* (*Charybdis*) *callianassa* (Herbst, 1789)	5	11	1	*Cancer callianassa* Herbst, 1789.
165	*Charybdis* (*Charybdis*) *feriata* (Linnaeus, 1758)	7	23	7	*Cancer cruciata* Herbst, 1794; *Cancer crucifer* Fabricius, 1792; *Cancer feriata* Linnaeus, 1758; *Cancer sexdentatus* Herbst, 1783; *Charybdis cruciata* (Herbst, 1794); *Charybdis sexdentata* (Herbst, 1783); *Portunus crucifer* Fabricius, 1798.
166	*Charybdis* (*Charybdis*) *granulata* (De Haan, 1833 [in De Haan, 1833–1850])	6	9	2	*Charybdis* (*Charybdis*) *moretonensis* Rees & Stephenson, 1966; *Portunus* (*Charybdis*) *granulata* De Haan, 1833 [in De Haan, 1833–1850].
167	*Charybdis* (*Charybdis*) *hellerii* (A. Milne Edwards, 1867)	10	35	4	*Charybdis merengiensis* (de Man); *Charybdis merguiensis* de Man, 1887; *Charybdis vannamei* Ward, 1941; *Goniosoma hellerii* A. Milne Edwards, 1867.
168	*Charybdis* (*Charybdis*) *lucifera* (Fabricius, 1798)	7	10	2	*Goniosoma quadrimaculatum* A. Milne Edwards, 1861; *Portunus lucifera* Fabricius, 1798.
169	*Charybdis* (*Charybdis*) *miles* (De Haan, 1835 [in De Haan, 1833–1850])	5	10	2	*Charybdis* (*Gonioneptunus*) *investigatoris* Alcock, 1899; *Portunus* (*Charybdis*) *miles* De Haan, 1835 [in De Haan, 1833–1850].
170	*Charybdis* (*Charybdis*) *orientalis* Dana, 1852	7	12	1	*Goniosoma dubium* Hoffman, 1874.
171	*Charybdis* (*Charybdis*) *riversandersoni* Alcock, 1899	5	7	0	_
172	*Charybdis* (*Charybdis*) *rostrata* (A. Milne Edwards, 1861)	2	4	1	*Goniosoma rostratum* A. Milne Edwards, 1861 (basionym).
173	*Charybdis* (*Charybdis*) *variegata* (Fabricius, 1798)	6	16	3	*Charybdis* (*Goniosoma*) *variegata* Fabricius, 1798); *Charybdis variegata* (Fabricius, 1798); *Portunus variegata* Fabricius, 1798.
174	*Charybdis* (*Goniohellenus*) *acutifrons* (de Man, 1879)	2	2	2	*Charybdis* (*Goniosupradens*) *acutifrons* (de Man, 1879); *Goniosoma acutifrons* de Man, 1879.
175	*Charybdis* (*Goniohellenus*) *hoplites* (Wood Mason, 1877)	3	8	2	*Archias sexdentatus* Paulson, 1875; *Goniosoma hoplites* Wood Mason, 1877.

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synonyms	Synonyms
176	*Charybdis* (*Goniohellenus*) *truncata* (Fabricius, 1798)	6	17	1	*Portunus truncata* Fabricius, 1798.
177	*Charybdis* (*Goniohellenus*) *vadorum* Alcock, 1899	3	9	1	*Charybdis* (*Goniohellenus*) *sinensis* Gordon, 1930.
178	*Lissocarcinus arkati* Kemp, 1923	5	6	0	–
179	*Lupocycloporus gracilimanus* (Stimpson, 1858)	5	12	3	*Achelous whitei* A. Milne-Edwards, 1861; *Amphitrite gracilimanus* Stimpson, 1858 (basionym); *Portunus* (*Lupocycloporus*) *gracilimanus* (Stimpson, 1858).
180	*Podophthalmus vigil* (Fabricius, 1798)	8	25	2	*Podophthalmus spinosus* Lamarck, 1801; *Portunus vigil* Fabricius, 1798.
181	*Monomia gladiator* (Fabricius, 1798)	6	14	1	*Portunus* (*Monomia*) *gladiator* Fabricius, 1798.
182	*Portunus pelagicus* (Linnaeus, 1758)	7	35	9	*Cancer cedonulli* Herbst, 1794; *Cancer pelagicus* Forskål, 1775; *Cancer pelagicus* Linnaeus, 1758; *Lupa pelagica* (Linnaeus, 1758); *Neptunus pelagicus* (Linnaeus, 1758); *Portunus* (*Portunus*) *pelagicus* (Linnaeus, 1758); *Portunus* (*Portunus*) *pelagicus var. sinensis* Shen, 1932; *Portunus denticulatus* Marion de Procé, 1822; *Portunus pelagicus var. sinensis* (Shen, 1932).
183	*Portunus pubescens* (Dana, 1852)	7	11	3	*Lupa pubescens* Dana, 1852; *Neptunus tomentosus* Haswell, 1881; *Portunus* (*Portunus*) *pubescens* (Dana, 1852).
184	*Portunus sanguinolentus* (Herbst, 1783)	8	35	8	*Callinectes alexandri* Rathbun, 1907; *Cancer gladiator* Fabricius, 1793; *Cancer raihoae* Curtiss, 1938; *Cancer sanguinolentus* Herbst, 1783; *Lupa sanguinolentus* (Herbst, 1783); *Portunus* (*Portunus*) *sanguinolentus* (Herbst, 1783); *Portunus* (*Portunus*) *sanguinolentus sanguinolentus* (Herbst, 1783); *Portunus sanguinolentus sanguinolentus* (Herbst, 1783).
185	*Xiphonectes hastatoides* (Fabricius, 1798)	8	21	3	*Neptunus* (*Hellenus*) *hastatoides* (Fabricius, 1798); *Neptunus* (*Hellenus*) *hastatoides var. unidens* Laurie, 1906; *Portunus* (*Xiphonectes*) *hastatoides* Fabricius, 1798.
186	*Xiphonectes pulchricristatus* (Gordon, 1931)	6	13	3	*Neptunus* (*Hellenus*) *alcocki* Gordon, 1930; *Neptunus* (*Hellenus*) *pulchricristatus* Gordon, 1931; *Portunus* (*Xiphonectes*) *pulchricristatus* (Gordon, 1931).
187	*Scylla olivacea* (Herbst, 1796)	4	10	1	*Cancer olivacea* Herbst, 1796.

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synonyms	Synonyms
188	*Scylla tranquebarica* (Fabricius, 1798)	5	9	6	*Amphitrite media* Stimpson, 1858; *Callinectes alcocki* P. S. Chen, 1933; *Callinectes platei* P. S. Chen, 1933; *Cancer defensor* Fabricius, 1787; *Cancer tranquebarica* Fabricius, 1798; *Portunus tranquebaricus* Latreille in Milbert, 1812.
189	*Thalamita admete* (Herbst, 1803)	8	39	5	*Cancer admete* Herbst, 1803; *Portunus integifrons* Marion de Procé, 1822; *Thalamita admete var. edwardsi* Borradaile, 1900; *Thalamita dispar* Rathbun, 1914; *Thalamita edwardsi* Borradaile, 1900.
190	*Thalamita chaptalii* (Audouin, 1826)	7	23	3	*Portunus chaptalii* Audouin, 1826 (basionym) *Thalamita chaptali* (Audouin & Savigny, 1817); *Thalamita holdsworthi* Miers, 1884.
191	*Thalamita prymna* (Herbst, 1803)	8	37	4	*Cancer prymna* Herbst, 1803; *Thalamita crassimana* Dana, 1852; *Thalamita gurjanovae* Tien, 1969;*Thalamita prymna var. annectans* Laurie, 1906.
192	*Thalamita danae* Stimpson, 1858	8	28	2	*Thalamita prymna var. proxima* Montgomery, 1931; *Thalamita stimpsoni* A. Milne Edwards, 1861 (basionym).
193	*Scylla paramamosain* Estampador, 1950	3	7	0	-
Pinnotheridae (5 spp.)		1-2	1-3	0-2	
194	*Austinixa leptodactyla* (Coelho, 1997)	1	1	1	*Pinnixa leptodactyla* Coelho, 1997.
195	*Arcotheres sinensis* (Shen, 1932)	2	2	1	*Pinnotheres sinensis* Shen, 1932 (basionym).
196	*Nepinnotheres cardii* (Bürger, 1895)	1	1	2	*Pinnotheres cardii* Bürger, 1895 (basionym); *Pinnotheres socius* Lanchester, 1902.
197	*Pinnotheres mactricola* Alcock, 1900	1	1	0	-
198	*Scleroplax granulata* Rathbun, 1894	2	3	1	*Scleroplax granulatus* Rathbun, 1894 (basionym).
Macrophthalmidae (22 spp.)		1–8	1–21	0–5	
199	*Macrophthalmus depressus* Rüppell, 1830	5	16	2	*Macrophthalmus affinis* Guérin-Méneville, 1838; *Macrophthalmus depressus* Rüppell, 1830 (basionym).
200	*Macrophthalmus grandidieri* A. Milne Edwards, 1867	2	6	0	_
201	*Macrophthalmus milloti* Crosnier, 1965	5	6	1	*Macrophthalmus milloti* Crosnier, 1965 (basionym).

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synony ms	Synonyms
202	*Macrophthalmus parvimanus* Guérin, 1834	3	4	4	*Aërope bidens* Leach in White, 1847; *Macrophthalmus parvimanus* Guérin, 1832; *Macrophthalmus parvimanus kempi* Gravely, 1927; *Ocypoda microcheles* Bosc, 1801.
203	*Ilyograpsus paludicola* (Rathbun, 1909)	5	5	1	*Camptandrium paludicola* Rathbun, 1909 (basionym).
204	*Macrophthalmus* (*Macrophthalmus*) *telescopicus* (Owen, 1839)	8	15	4	*Gelasimus telescopicus* Owen, 1839; *Macrophthalmus compressipes* Randall, 1840 ; *Macrophthalmus podophthalmus* Eydoux & Souleyet, 1842; *Macrophthalmus verreauxi* H. Milne Edwards, 1848.
205	*Chaenostoma boscii* (Audouin, 1826)	6	14	3	*Macrophthalmus* (*Chaenostoma*) *boscii* Audouin, 1826; *Macrophthalmus Boscii* Audouin, 1826 (basionym); *Macrophthalmus Franchettii* Maccagno, 1936.
206	*Macrophthalmus* (*Macrophthalmus*) *abbreviatus* R.B. Manning & Holthuis, 1981	4	7	2	*Macrophthalmus dilatatus* De Haan, 1835 [in De Haan, 1833–1850] ; *Ocypode* (*Macrophthalmus*) *dilatata* De Haan, 1835 [in De Haan, 1833–1850].
207	*Macrophthalmus* (*Macrophthalmus*) *brevis* (Herbst, 1804)	4	8	5	*Cancer brevis* Herbst, 1804; *Macrophthalmus carinimanus* H. Milne Edwards, 1837; *Macrophthalmus dilatatus carens* Lanchester, 1900; *Macrophthalmus simdentatus* Shen, 1936 ; *Macrophthalmus travancorensis* N.K. Pillai, 1951.
208	*Macrophthalmus* (*Macrophthalmus*) *convexus* Stimpson, 1858	6	21	2	*Macrophthalmus convexus* Stimpson, 1858 (basionym); *Macrophthalmus inermis* A. Milne Edwards, 1867.
209	*Macrophthalmus* (*Macrophthalmus*) *crassipes* H. Milne Edwards, 1852	3	4	0	_
210	*Macrophthalmus* (*Macrophthalmus*) *transverses* (Latreille, 1817)	2	4	1	*Goneplax transversus* Latreille, 1817.
211	*Macrophthalmus* (*Mareotis*) *crinitus* Rathbun, 1913	3	5	1	*Macrophthalmus crinitus* Rathbun, 1913 (basionym).
212	*Macrophthalmus* (*Mareotis*) *pacificus* Dana, 1851	4	7	1	*Macrophthalmus bicarinatus* Heller, 1862 (junior synonym).
213	*Macrophthalmus* (*Mareotis*) *teschi* Kemp, 1919	2	4	1	*Macrophthalmus teschi* Kemp, 1919 (basionym).
214	*Macrophthalmus* (*Mareotis*) *tomentosus* Eydoux & Souleyet, 1842	2	6	0	_

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synonyms	Synonyms
208	*Macrophthalmus* (*Macrophthalmus*) *convexus* Stimpson, 1858	6	21	2	*Macrophthalmus convexus* Stimpson, 1858 (basionym); *Macrophthalmus inermis* A. Milne Edwards, 1867.
209	*Macrophthalmus* (*Macrophthalmus*) *crassipes* H. Milne Edwards, 1852	3	4	0	_
210	*Macrophthalmus* (*Macrophthalmus*) *transverses* (Latreille, 1817)	2	4	1	*Goneplax transversus* Latreille, 1817.
211	*Macrophthalmus* (*Mareotis*) *crinitus* Rathbun, 1913	3	5	1	*Macrophthalmus crinitus* Rathbun, 1913 (basionym).
212	*Macrophthalmus* (*Mareotis*) *pacificus* Dana, 1851	4	7	1	*Macrophthalmus bicarinatus* Heller, 1862 (junior synonym).
213	*Macrophthalmus* (*Mareotis*) *teschi* Kemp, 1919	2	4	1	*Macrophthalmus teschi* Kemp, 1919 (basionym).
214	*Macrophthalmus* (*Mareotis*) *tomentosus* Eydoux & Souleyet, 1842	2	6	0	_
208	*Macrophthalmus* (*Macrophthalmus*) *convexus* Stimpson, 1858	6	21	2	*Macrophthalmus convexus* Stimpson, 1858 (basionym); *Macrophthalmus inermis* A. Milne Edwards, 1867.
209	*Macrophthalmus* (*Macrophthalmus*) *crassipes* H. Milne Edwards, 1852	3	4	0	_
210	*Macrophthalmus* (*Macrophthalmus*) *transverses* (Latreille, 1817)	2	4	1	*Goneplax transversus* Latreille, 1817.
211	*Macrophthalmus* (*Mareotis*) *crinitus* Rathbun, 1913	3	5	1	*Macrophthalmus crinitus* Rathbun, 1913 (basionym).
212	*Macrophthalmus* (*Mareotis*) *pacificus* Dana, 1851	4	7	1	*Macrophthalmus bicarinatus* Heller, 1862 (junior synonym).
213	*Macrophthalmus* (*Mareotis*) *teschi* Kemp, 1919	2	4	1	*Macrophthalmus teschi* Kemp, 1919 (basionym).
214	*Macrophthalmus* (*Mareotis*) *tomentosus* Eydoux & Souleyet, 1842	2	6	0	_

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synonyms	Synonyms
215	*Macrophthalmus* (*Para-mareotis*) *erato* de Man, 1887 [in de Man, 1887–1888]	4	9	1	*Macrophthalmus erato* de Man, 1887 [in de Man, 1887–1888].
216	*Venitus dentipes* (Lucas in Guerin Meneville, 1836)	3	3	5	*Macrophthalmus dentipes* Lucas, 1836; *Macrophthalmus guerini* H. Milne Edwards, 1852; *Macrophthalmus pectinipes* Guérin- Méneville, 1838; *Macrophthalmus rouxii* Lucas, 1836; *Macrophthalmus simplicipes* Guérin- Méneville, 1838.
217	*Macrophthalmus* (*Para-mareotis*) *quadratus* A. Milne Edwards, 1873	4	6	1	*Macrophthalmus quadratus* A. Milne Edwards, 1873 (basionym).
218	*Macrophthalmus latreillii* (Desrnarest, 1822)	7	16	0	_
219	*Apograpsus paantu* (Naruse & Kishino, 2006)	1	1	1	*Ilyograpsus paantu* Naruse & Kishino, 2006.
220	*Ilyograpsus nodulosus* T. Sakai, 1983	2	2	0	_
Dotillidae (18 spp.)		1–3	1–8	0–1	
221	*Dotilla fenestrata* Hilgendorf, 1869	2	6	1	*Dotilla clepsydra* Stebbing, 1917.
222	*Dotilla blandfordi* Alcock, 1900	1	2	0	-
223	*Ilyoplax frater* (Kemp, 1919)	1	1	1	*Tympanomerus frater* Kemp, 1919 (basionym).
224	*Scopimera crabicauda* Alcock, 1900	1	3	0	-
225	*Dotilla wichmanni* de Man, 1892	3	8	0	-
226	*Ilyoplax delsmani* de Man, 1926	2	5	0	-
227	*Ilyoplax lingulata* (Rathbun, 1909)	1	3	1	*Cleistostoma lingulatum* Rathbun, 1909 (basio-nym).
228	*Ilyoplax longicarpa* Tweedie, 1937	1	1	0	_
229	*Ilyoplax obliqua* Tweedie, 1935	1	2	0	_
230	*Ilyoplax orientalis* (de Man, 1888 [in de Man, 1887–1888])	2	5	1	*Dioxippe orientalis* de Man, 1888 [in de Man, 1887–1888] (basionym).
231	*Ilyoplax punctata* Tweedie, 1935	1	3	0	_
232	*Scopimera intermedia* Balss, 1934	2	5	1	*Sphaerapoeia collingwoodii* Collingwood, 1868.
233	*Shenius anomalus* (Shen, 1935)	1	1	1	*Camptandrium anomalum* Shen, 1935 (basio-nym).
234	*Ilyoplax strigicarpus* Davie, 1990	2	2	0	_

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synonyms	Synonyms
235	*Tmethypocoelis odonto-dactylus* Davie, 1990	2	2	0	_
236	*Tmethypocoelis choreutes* Davie & Kosuge, 1995	1	1	0	_
237	*Ilyoplax pusilla* (De Haan, 1835 [in De Haan, 1833–1850])	1	1	1	*Ocypode* (*Cleistostoma*) *pusilla* De Haan, 1835 [in De Haan, 1833–1850]
238	*Scopimera ryukyuensis* Wong, Chan & Shih, 2010	1	2	0	-
Varunidae (21 spp.)		1–7	1–32	0–3	
239	*Metaplax indica* H. Milne Edwards,1852	3	5	0	-
240	*Pseudograpsus interme-dius* Chhapgar, 1957	1	1	0	-
241	*Hemigrapsus oregonensis* (Dana, 1851)	2	3	1	*Pseudograpsus oregonensis* Dana, 1851.
242	*Metaplax crenulata* (Gerstaecker, 1856)	2	5	1	*Rhaconotus crenulata* Gerstaecker, 1856.
243	*Metaplax dentipes* (Heller, 1865)	2	3	1	*Helice dentipes* Heller, 1865.
244	*Metaplax distincta* H. Milne Edwards, 1852	2	3	0	-
245	*Metaplax elegans* de Man, 1888	3	11	1	*Metaplax crassipes* de Man, 1892.
246	*Metaplax intermedia* de Man, 1888	1	1	1	*Metaplax intermedius* de Man, 1888 [in de Man, 1887-1888] (basionym).
247	*Parapyxidognathus deianira* (de Man, 1888)	4	4	1	*Pyxidognathus deianira* de Man, 1888.
248	*Ptychognathus altimanus* (Rathbun, 1914)	4	8	1	*Varuna altimana* Rathbun, 1914 (basionym).
249	*Ptychognathus barbatus* (A. Milne-Edwards, 1873)	4	10	1	*Gnathograpsus barbatus* A. Milne Edwards, 1873 (basionym).
250	*Ptychognathus dentatus* de Man, 1892	2	3	1	-
251	*Ptychognathus onyx* Alcock, 1900	3	4	0	-
252	*Pyxidognathus fluviatilis* Alcock, 1900	1	1	0	-
253	*Varuna litterata* (Fabricius, 1798)	7	32	3	*Cancer litterata* Fabricius, 1798; *Cancer simmonsi* Curtiss, 1938; *Varuna tomentosa* Pfeffer, 1889.
254	*Metaplax sheni* Gordon, 1930	1	3	0	-
255	*Utica borneensis* de Man, 1895 [in de Man, 1895–1898]	3	5	0	-

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synonyms	Synonyms
256	*Varuna yui* Hwang & Takeda, 1986	3	8	0	-
257	*Metaplax longipes* Stimpson, 1858	2	2	1	*Metaplax takahashii* T. Sakai, 1939.
258	*Pseudohelice subquadrata* (Dana, 1851)	7	17	3	*Chasmagnathus subquadratus* Dana, 1851; *Helice leachi* Hess, 1865; *Helice Leachii* Hess, 1865.
259	*Paragrapsus laevis* (Dana, 1851)	1	1	2	*Chasmagnathus laevis* Dana, 1851; *Paragrapsus verreauxi* H. Milne Edwards, 1853.
Oziidae (4 spp.)		4–8	6–27	2–5	
260	*Epixanthus dentatus* (White, 1848)	6	17	3	*Epixanthus dilatatus* de Man, 1879; *Panopeus acutidens* Haswell, 1881; *Panopeus dentatus* White, 1848.
261	*Baptozius vinosus* (H. Milne Edwards, 1834)	4	6	2	*Rueppellia lata* A. Milne Edwards, 1873; *Rueppellia vinosus* H. Milne Edwards, 1834.
262	*Lydia annulipes* (H. Milne Edwards, 1834)	8	27	4	*Euruppellia annulipes* (H. Milne Edwards, 1834); *Euxanthus rugulosus* Heller, 1865; *Lydia danae* Ward, 1939; *Rueppellia annulipes* H. Milne Edwards, 1834.
263	*Ozius guttatus* H. Milne Edwards, 1834	5	17	5	*Cancer* (*Eudora*) *incisus* De Haan, 1833 [in De Haan, 1833–1850] ; *Ozius guttatus garciaensis* Ward, 1942; *Ozius speciosus* Hilgendorf, 1869; *Panopeus formio* Adams & White, 1849; *Panopeus formio* White, 1847.
Pilumnidae (15 spp.)		1–8	1–36	0–4	
264	*Eurycarcinus natalensis* (Krauss, 1843)	4	11	2	*Cancer* (*Galene*) *natalensis* Krauss, 1843 (basionym); *Eurycarcinus grandidierii* A. Milne Edwards, 1867.
265	*Eurycarcinus orientalis* A. Milne Edwards, 1867	3	9	0	-
266	*Benthopanope indica* (de Man, 1887 [in de Man, 1887-1888])	2	2	1	*Heteropanope indica* de Man, 1887 [in de Man, 1887-1888] (basionym).
267	*Heteropanope bengalensis* (Deb, 1999)	1	1	1	*Eurycarcinus bengalensis* Deb, 1999 (basionym).
268	*Heteropanope glabra Stimpson, 1858*	7	14	1	*Pilumnopeus maculatus* A. Milne Edwards, 1867.
269	*Heteropanope neolaevis Deb, 1995*	1	1	0	-
270	*Heteropilumnus angustifrons* (Alcock, 1900)	1	1	1	*Litochira angustifrons* Alcock, 1900.
271	*Heteropilumnus ciliatus* (Stimpson, 1858)	2	3	2	*Heteropanope cristadentatus* Shen, 1936; *Pilumnoplax ciliatus* Stimpson, 1858 (basionym).
272	*Pseudocryptocoeloma andamanicus* (Deb, 1989)	1	1	1	*Myopilumnus andamanicus* Deb, 1989 (basionym).
273	*Pilumnus cursor* A. Milne Edwards, 1873	5	11	0	-

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synony ms	Synonyms
274	*Pilumnus vespertilio* (Fabricius, 1793)	8	36	4	*Actaea dentata* Edmondson, 1935; *Cancer vespertilio* Fabricius, 1793; *Pilumnus mus* Dana, 1825; *Pilumnus ursulus* Adams & White, 1849.
275	*Typhlocarcinus nudus* Stimpson, 1858	3	5	0	-
276	*Aniptumnus quadridenta-tus* (de Man, 1895 [in de Man, 1895–1898])	1	2	3	*Parapilumnus quadridentatus* (De Man, 1895); *Pilumnopeus riui* Takeda, 2001; *Pilumnus* (*Para-pilumnus*) *quadridentatus* de Man, 1895 [in de Man, 1895–1898] (basionym).
277	*Luteocarcinus*	1	2	0	-
267	*Heteropanope bengalensis* (Deb, 1999)	1	1	1	*Eurycarcinus bengalensis* Deb, 1999 (basio-nym).
268	*Heteropanope glabra Stimpson, 1858*	7	14	1	*Pilumnopeus maculatus* A. Milne Edwards, 1867.
269	*Heteropanope neolaevis Deb, 1995*	1	1	0	-
270	*Heteropilumnus angusti-frons* (Alcock, 1900)	1	1	1	*Litochira angustifrons* Alcock, 1900.
271	*Heteropilumnus ciliatus* (Stimpson, 1858)	2	3	2	*Heteropanope cristadentatus* Shen, 1936; *Pilumnoplax ciliatus* Stimpson, 1858 (basio-nym).
272	*Pseudocryptocoeloma andamanicus* (Deb, 1989)	1	1	1	*Myopilumnus andamanicus* Deb, 1989 (basio-nym).
273	*Pilumnus cursor* A. Milne Edwards, 1873	5	11	0	-
274	*Pilumnus vespertilio* (Fabricius, 1793)	8	36	4	*Actaea dentata* Edmondson, 1935; *Cancer vespertilio* Fabricius, 1793; *Pilumnus mus* Dana, 1825; *Pilumnus ursulus* Adams & White, 1849.
275	*Typhlocarcinus nudus* Stimpson, 1858	3	5	0	-
276	*Aniptumnus quadridenta-tus* (de Man, 1895 [in de Man, 1895–1898])	1	2	3	*Parapilumnus quadridentatus* (De Man, 1895); *Pilumnopeus riui* Takeda, 2001; *Pilumnus* (*Para-pilumnus*) *quadridentatus* de Man, 1895 [in de Man, 1895–1898] (basionym).
277	*Luteocarcinus sordidus* Ng, 1990	1	2	0	-
278	*Pilumnopeus marginatus* (Stimpson, 1858)	2	2	1	*Pilumnus marginatus* Stimpson, 1858 (basio-nym).
Coenobitidae (2 spp.)		7–9	26–41	2–4	
279	*Coenobita rugosus* H. Milne Edwards, 1837	9	41	4	*Cenobita rugosa* H. Milne Edwards, 1837 (bas-ionym); *Coenobita rugosa* H. Milne Edwards, 1837; *Coenobita rugosa var. wagneri* Doflein, 1900; *Coenobita subrugosa* Neumann, 1878.
280	*Coenobita cavipes* Stimpson, 1858	7	26	2	*Cenobita cavipes* Stimpson, 1858; *Coenobita Baltzeri* Neumann, 1878.
Goneplacidae (1 spp.)					

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synony ms	Synonyms
281	*Goneplax rhomboides* (Linnaeus, 1758)	4	7	8	*Cancer angulata* Pennant, 1777; *Cancer rhomboides* Linnaeus, 1758; *Gelasimus bellii* Couch, 1838; *Goneplax angulata* (Pennant, 1777); *Goneplax rhomboidalis* Risso, 1827 in [Risso, 1826–1827]; *Ocypoda bispinosa* Lamarck, 1801 *Ocypoda unispinosa* Rafinesque, 1814; *Ocypode longimana* Latreille, 1803.
Scalopidiidae (1 spp.)					
282	*Scalopidia spinosipes* Stimpson, 1858	2	6	2	*Hypophthalmus leuchochirus* Richters in Lenz & Richters, 1881; *Scalopidia leuchochirus* (Richters, 1881).
Iphiculidae (2 spp.)		6–7	8–14	0–2	
283	*Iphiculus spongiosus* Adams & White, 1848	7	14	0	-
284	*Pariphiculus mariannae* (Herklots, 1852)	6	8	2	*Ilia mariannae* Herklots, 1852; *Pariphiculus rostratus* Alcock, 1896.
Leucosiidae (14 spp)		1–7	1–23	1–6	
285	*Arcania erinacea* (Fabricius, 1787)	2	3	1	*Cancer erinacea* Fabricius, 1787.
286	*Arcania septemspinosa* (Fabricius, 1787)	7	12	4	*Arcania siamensis* Rathbun, 1909; *Cancer hystrix* Fabricius, 1793; *Cancer septemspinosa* Fabricius, 1787; *Iphis longipes* Dana, 1852.
287	*Euclosiana rotundifrons* (Chopra, 1933)	1	1	2	*Euclosia rotundifrons* (Chopra, 1933); *Leucosia rotundifrons* Chopra, 1933.
288	*Ixa cylindrus* (Fabricius, 1777)	5	11	4	*Cancer cylindrus* Fabricius, 1777 ; *Ixa canaliculata* Leach, 1817; *Ixa cylindricus* (Fabricius, 1777); *Ixa megaspis* Adams & White, 1849.
289	*Ixa inermis* Leach, 1817	3	3	0	-
290	*Leucosia craniolaris* (Linnaeus, 1758)	7	12	6	*Cancer craniolaris* Linnaeus, 1758; *Leucosia obscura* Bell, 1855; *Leucosia obscura* White, 1847; *Leucosia pallida* Bell, 1855; *Leucosia parvimana* Stimpson, 1858 (basionym); *Leucosia perlata* De Haan, 1841 [in De Haan, 1833–1850].
291	*Myra elegans* Bell, 1855	5	8	0	-
292	*Myra fugax* (Fabricius, 1798)	7	23	6	*Cancer punctatus* Herbst, 1783; *Leucosia fugax* Fabricius, 1798 (Basionym); *Myra carinata* Bell, 1855; *Myra carinata* White, 1847; *Myra longimerus* Chen & Türkay, 2001; *Myra pentacantha* Alcock, 1896.
293	*Parilia alcocki* Wood-Mason in Wood Mason & Alcock, 1891	4	6	0	-

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synony ms	Synonyms
294	*Philyra globus* (Fabricius, 1775)	6	9	5	*Cancer globosus* Fabricius, 1793; *Cancer globus* Fabricius, 1775; *Leucosia globulosus* Bosc, 1801; *Philyra globulosa* H. Milne Edwards, 1837; *Philyra polita* Henderson, 1893 (junior synonym).
295	*Philyra sexangula* Alcock, 1896	1	2	0	-
296	*Seulocia rhomboidalis* (De Haan, 1841 [in De Haan, 1833–1850])	5	10	2	*Leucosia maculata* Stimpson, 1858 (basionym); *Leucosia rhomboidalis* De Haan, 1841 [in De Haan, 1833–1850].
297	*Praosia punctata* Tan & Ng, 1993	1	1	0	-
298	*Philyra nishihirai* Takeda & Nakasone, 1991	1	1	0	-
Epialtidae (7 spp.)		2–7	6–14	1–4	
299	*Doclea armata* De Haan, 1839 [in De Haan, 1833–1850]	2	7	2	*Doclea calcitrapa* White, 1847; *Doclea tetraptera* Walker, 1887 (junior synonym).
300	*Doclea canalifera* Stimpson, 1857	3	6	1	*Doclea japonica* Ortmann, 1893.
301	*Doclea muricata* (Herbst, 1787)	3	6	4	*Cancer muricata* Herbst, 1788; *Doclea hybridoidea* Bleeker, 1856; *Inachus hybridus* Fabricius, 1798; *Inachus hybridus* Weber, 1795.
302	*Doclea rissoni* Leach, 1815	2	6	4	*Doclea Andersoni* de Man, 1887 [in de Man, 1887-1888] ; *Doclea gracilipes* Stimpson, 1858; *Doclea sebae* Bleeker, 1856; *Doclea sinensis* Dai, 1981.
303	*Doclea ovis* (Fabricius, 1787)	4	9	1	*Cancer ovis* Fabricius, 1787.
304	*Hyastenus diacanthus* (De Haan, 1839)	7	14	1	*Pisa* (*Naxia*) *diacanthus* De Haan, 1839 [in De Haan, 1833–1850].
305	*Phalangipus longipes* (Linnaeus, 1758)	7	14	3	*Cancer arachnoides* Linnaeus, 1758; *Cancer lar* Fabricius, 1793; *Cancer longipes* Linnaeus, 1758.
Hymenosomitidae (8 spp.)		1–5	1–8	0–1	
306	*Elamena truncata* (Stimpson, 1858)	4	8	1	*Trigonoplax truncatus* Stimpson, 1858 (basionym).
307	*Hymenicoides carteri* Kemp, 1917	1	1	0	-
308	*Neorhynchoplax inachoides* (Alcock, 1900)	1	1	1	*Hymenicus inachoides* Alcock, 1900.
309	*Neorhynchoplax nasalis* (Kemp, 1917)	1	1	1	*Rhynchoplax nasalis* Kemp, 1917 (basionym).
310	*Neorhynchoplax octagonalis* (Kemp, 1917)	1	1	1	*Rhynchoplax octagonalis* Kemp, 1917 (basionym).

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synony ms	Synonyms
311	*Neorhynchoplax woodmasoni* (Alcock,1900)	1	1	1	*Hymenicus woodmasoni* Alcock, 1900.
312	*Trigonoplax unguiformis* (De Haan, 1839 [in De Haan, 1833–1850])	5	5	1	*Inachus* (*Elamene*) *unguiformis* De Haan, 1839 [in De Haan, 1833–1850].
313	*Neorhynchoplax mangalis* (P.K.L. Ng, 1988)	1	1	1	*Elamenopsis mangalis* P.K.L. Ng, 1988 (basionym).
Parthenopidae (3 spp.)		1–6	2–15	1–4	
314	*Cryptopodia angulata* H. Milne Edwards & Lucas, 1841	3	3	1	*Cryptopodia angulata var. cippifer* Alcock, 1895.
315	*Enoplolambrus pransor* (Herbst, 1796)	1	2	4	*Cancer pransor* Herbst, 1796; *Lambrus jourdainii* Brito Capello, 1871; *Lambrus tumidus* Lanchester, 1900; *Parthenope regina* Fabricius, 1798.
316	*Parthenope longimanus* (Linnaeus, 1758)	6	15	4	*Cancer longimanus* Linnaeus, 1758; *Lambrus* (*Lambrus*) *ornatus* Flipse, 1930; *Lambrus laevicarpus* Miers, 1879; *Parthenope longimana* (Linnaeus, 1764).
Galenidae (3 spp.)		1-5	2-5	2-4	
317	*Halimede fragifer* (De Haan, 1835 [in De Haan, 1833–1850])	1	2	4	*Cancer* (*Halimede*) *fragifer* De Haan, 1835 [in De Haan, 1833–1850]; *Halimede dofleini* Balss, 1922 *Medaeus nodosus* A. Milne Edwards, 1867; *Medaeus nodulosus* A. Milne Edwards, 1873; (incorrect spelling).
318	*Halimede tyche* (Herbst, 1801)	5	5	3	*Cancer tyche* Herbst, 1801; *Halimede hendersoni* Nobili, 1905; *Halimede thurstoni* Henderson, 1893.
319	*Parapanope euagora* de Man, 1895 [in de Man, 1895–1898]	3	5	2	*Hoploxanthus hextii* Alcock, 1898; *Parapanope singaporensis* P.K.L. Ng & Guinot in Guinot, 1985.
Xanthidae (15 spp.)		1–8	1–41	0–7	
320	*Actaeodes tomentosus* (H. Milne Edwards, 1834)	8	35	2	*Actaea tomentosa* (H. Milne Edwards, 1834); *Zozymus tomentosus* H. Milne Edwards, 1834.
321	*Atergatis floridus* (Linnaeus, 1767)	8	30	1	*Cancer floridus* Linnaeus, 1767.
322	*Atergatis integerrimus* (Lamarck, 1818)	7	22	3	*Atergatis subdivisus* White, 1848; *Cancer integerrimus* Lamarck, 1818; *Cancer laevis latipes* Seba, 1761.
323	*Atergatis subdentatus* (De Haan, 1835 [in De Haan, 1833–1850])	4	8	1	*Cancer* (*Atergatis*) *subdentatus* De Haan, 1835 [in De Haan, 1833–1850].
324	*Etisus laevimanus* Randall, 1840	8	32	5	*Chlorodopsis espinosus* Borradaile, 1902; *Etisus convexus* Stimpson, 1858; *Etisus macrodactylus* Bianconi, 1851; *Etisus macrodactylus* Lucas in Jacquinot & Lucas, 1853; *Etisus maculatus* Heller, 1861.

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synony ms	Synonyms
325	*Demania armadillus* (Herbst, 1790 [in Herbst, 1782–1790])	1	1	3	*Cancer armadillus* Herbst, 1790 [in Herbst, 1782–1790] (basionym); *Demania bangladeshensis* P.K.L. Ng, Huda & Banu, 1987; *Demania indiana* Deb, 1987.
326	*Demania scaberrima* (Walker, 1887)	3	6	1	*Xantho scaberrimus* Walker, 1887 (basionym).
327	*Leptodius exaratus* (H. Milne Edwards, 1834)	7	41	4	*Cancer inaequalis* Audouin, 1826; *Chlorodius exaratus* H. Milne Edwards, 1834; *Leptodius lividus* Paulson, 1875; *Xantho exaratus* (H. Milne Edwards, 1834).
328	*Leptodius sanguineus* (H. Milne Edwards, 1834)	8	36	7	*Cancer eudora* Herbst, 1801; *Chlorodius edwardsii* Heller, 1861; *Chlorodius sanguineus* H. Milne Edwards, 1834; *Lagostoma nodosa* Randall, 1840 ; *Leptodius philippinensis* Ward, 1941; *Leptodius sanguineus philippinensis* Ward, 1941; *Xantho edwardsii* (Heller).
329	*Liagore erythematica* Guinot, 1971	1	1	0	-
330	*Macromedaeus crassimanus* (A. Milne Edwards, 1867)	7	15	2	*Leptodius crassimanus* (A.Milne Edwards, 1867); *Xantho crassimanus* A. Milne Edwards, 1867.
331	*Nectopanope rhodobaphes* Wood Mason in Wood Mason & Alcock, 1891	1	1	0	-
332	*Orphnoxanthus microps* (Alcock & Anderson, 1894)	1	1	1	*Xanthodes microps* Alcock & Anderson, 1894.
333	*Pilodius nigrocrinitus* Stimpson, 1858	5	13	1	*Chlorodopsis melanochirus* A. Milne Edwards, 1873 (junior synonym).
334	*Platypodia cristata* (A. Milne Edwards, 1865)	6	10	1	*Lophactaea cristata* A. Milne Edwards, 1865.
Plagusiidae (3 spp.)		3–9	3–35	2–6	
335	*Plagusia depressa* (Fabricius, 1775)	7	35	4	*Cancer depressa* Fabricius, 1775; *Plagusia depressa depressa* (Fabricius, 1775); *Plagusia gracilis* Saussure, 1858; *Plagusia sayi* De Kay, 1844.
336	*Plagusia squamosa* (Herbst, 1790)	9	31	6	*Cancer squamosa* Herbst, 1790; *Grapse tuberculatus* Latreille in Milbert, 1812; *Plagusia depressa squamosa* Lamarck.1818; *Plagusia depressa tuberculata* Lamarck, 1818; *Plagusia orientalis* Stimpson, 1858; *Plagusia tuberculata* Lamarck, 1818.
337	*Guinusia dentipes* (De Haan, 1835 [in De Haan, 1833–1850])	3	3	2	*Grapsus* (*Plagusia*) *dentipes* De Haan, 1835 [in De Haan, 1833–1850]; *Plagusia dentipes* (De Haan, 1835 [in De Haan, 1833–1850]).
Mictyridae (2 spp.)		1–5	1–10	0–1	

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synonyms	Synonyms
338	*Mictyris longicarpus* Latreille, 1806	5	10	1	*Ocypode* (*Mictyris*) *deflexifrons* De Haan, 1835 [in De Haan, 1833–1850].
339	*Mictyris guinotae* Davie, Shih & Chan, 2010	1	1	0	-
Camptandriidae (22 spp.)		1–3	1–7	0–4	
340	*Serenella leachii* (Audouin, 1826)	1	2	4	*Cleistostoma leachii* (Audouin, 1826); *Cleistostoma leachii var. penicillata* Paulson, 1875; *Macrophthalmus leachii* Audouin, 1826 (basionym); *Paracleistostoma leachii* (Audouin, 1826).
341	*Opusia indica* (Alcock, 1900)	2	2	1	*Tylodiplax indica* Alcock, 1900.
342	*Nasima dotilliformis* (Alcock, 1900)	2	3	2	*Cleistostoma dotilliformis* Alcock, 1900; *Clistostoma dotilliforme* Alcock, 1900.
343	*Baruna socialis* Stebbing, 1904	3	5	1	*Leipocten sordidulum* Kemp, 1915.
344	*Dotilla intermedia* de Man, 1888	2	3	1	*Dotilla clepsydrodactyla* Alcock, 1900.
345	*Dotilla myctiroides* (H. Milne Edwards, 1852)	2	7	1	*Doto myctiroides* H. Milne Edwards, 1852.
346	*Dotillopsis brevitarsis* (de Man, 1888 [in de Man, 1887–1888])	2	4	1	*Dotilla brevitarsis* de Man, 1888 [in de Man, 1887–1888] (basionym).
347	*Ilyoplax gangetica* (Kemp, 1919)	1	1	1	*Tympanomerus gangeticus* Kemp, 1919 (basionym).
348	*Ilyoplax stapletoni* (de Man, 1908)	2	3	1	*Tympanomerus stapletoni* de Man, 1908.
349	*Scopimera globosa* (De Haan, 1835 [in De Haan, 1833–1850])	2	5	2	*Ocypode* (*Scopimera*) *globosa* De Haan, 1835 [in De Haan, 1833–1850]; *Scopimera tuberculata* Stimpson, 1858.
350	*Scopimera investigatoris* Alcock, 1900	1	1	0	-
351	*Scopimera pilula* Kemp, 1919	2	3	0	-
352	*Scopimera proxima* Kemp, 1919	2	3	0	-
353	*Baruna trigranulum* (Dai & Song, 1986)	3	4	2	*Baruna mangromurphia* Harminto & P.K.L. Ng, 1991; *Leipocten trigranulum* Dai & Song, 1986.
354	*Moguai elongatum* (Rathbun, 1931)	2	3	1	*Camptandrium elongatum* Rathbun, 1931 (basionym).
355	*Ilyogynnis microcheirum* (Tweedie, 1937)	1	3	1	*Paracleistostoma microcheirum* Tweedie, 1937 (basionym).
356	*Paracleistostoma depressum* de Man, 1895 [in de Man, 1895–1898]	2	5	0	-
357	*Paracleistostoma wardi* (Rathbun, 1926)	1	1	1	*Cleistostoma wardi* Rathbun, 1926 (basionym).
358	*Tylodiplax tetralyphora* de Man, 1895	1	2	0	-

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synonyms	Synonyms
359	*Paracleistostoma longimanum* Tweedie, 1937	1	3	0	-
360	*Takedellus ambonense* (Serène & Moosa, 1971)	1	1	1	*Camptandrium ambonensis* Serène & Moosa, 1971 (basionym); *Camptandrium rathbunae* Takeda, 1971.
361	*Mortensenella forceps* Rathbun, 1909	2	3	0	-
Heloeciidae (1 spp.)					
362	*Heloecius cordiformis* (H. Milne Edwards, 1837)	2	2	4	*Gelasimus cordiformis* H. Milne Edwards, 1837; *Heloecius areolatus* Heller, 1862; *Heloecius inornatus* Dana, 1851; *Heloecius signatus* Hess, 1865.
Clappidae (2 spp.)		5–7	9–19	0–1	
363	*Calappa lophos* (Herbst, 1782)	7	19	1	*Cancer lophos* Herbst, 1782.
364	*Calappa pustulosa* Alcock, 1896	5	9	0	-
Matutidae (4 spp.)		4–7	7–30	1–7	
365	*Ashtoret lunaris* (Forskål, 1775)	7	30	4	*Cancer lunaris* Forskål, 1775; *Matuta banksi* Leach, 1817; *Matuta banksii* Leach, 1817; *Matuta lunaris* (Forskål, 1775).
366	*Ashtoret miersii* (Henderson, 1887)	4	7	1	*Matuta miersii* Henderson, 1887.
367	*Matuta planipes* Fabricius, 1798	7	16	7	*Cancer americanus* Seba, 1758; *Cancer lunaris* Herbst, 1783; *Matuta appendiculata* Bosc, 1830; *Matuta flagra* Shen, 1936; *Matuta laevidactyla* Miers, 1880; *Matuta lineifera* Miers, 1877; *Matuta rubrolineata* Miers, 1877.
368	*Matuta victor* (Fabricius, 1781)	7	27	5	*Cancer victor* Fabricius, 1781; *Matuta lesueurii* Leach, 1817; *Matuta peronii* Leach, 1817; *Matuta victrix* (Fabricius, 1781) ; *Matuta victrix crebripunctata* Miers, 1877.
Corystidae (1 spp.)					
369	*Jonas indicus* (Chopra, 1935)	1	1	1	*Gomeza indicus* Chopra, 1935.
Corpilidae (2 spp.)		8–9	29–43	2–5	
370	*Carpilius convexus* (Forskål, 1775)	9	43	5	*Cancer adspersus* Herbst, 1790; *Cancer convexus* Forskål, 1775; *Cancer petraeus* Herbst, 1801; *Cancer samuelis* Curtiss, 1938; *Carpilius lividus* Gibbes, 1850 (junior synonym).
371	*Carpilius maculatus* (Linnaeus, 1758)	8	29	2	*Cancer maculatus* Linnaeus, 1758; *Cancer nepotei* Curtiss, 1938.
Menippidae (2 spp.)		3–5	7–9	2–5	
372	*Menippe rumphii* (Fabricius, 17d98)	5	9	2	*Cancer rumphii* Fabricius, 1798; *Pseudocarcinus bellangerii* H. Milne Edwards, 1834.

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synony ms	Synonyms
373	*Myomenippe hardwickii* (Gray, 1831)	3	7	5	*Cancer hardwickii* Gray, 1831; *Menippe* (*Myomenippe*) *duplicidens* Hilgendorf, 1879; *Menippe granulosa* A. Milne Edwards, 1867; *Menippe granulosa* de Man, 1888; *Myomenippe hardwicki* (Gray, 1831).
Ethusidae (1 spp.)					
374	*Ethusa indica* Alcock, 1894	5	8	1	*Ethusa serenei* T. Sakai, 1983.
Eriphiidae (4 spp.)		4–6	14–41	2–7	
375	*Eriphia sebana* (Shaw & Nodder, 1803)	6	41	7	*Cancer sebana* Shaw & Nodder, 1803; *Cancer tearlachi* Curtiss, 1938; *Eriphia fordii* MacLeay, 1838; *Eriphia laevimana* Guérin, 1832; *Eriphia sebana hawaiiensis* Ward, 1939; *Eriphia trapeziformis* Hess, 1865; *Gecarcinus anisocheles* Latreille, 1818.
376	*Eriphia smithii* MacLeay, 1838	4	18	2	*Eriphia sebana smithii* McLeay, 1838; *Eriphia smithi* McLeay, 1838.
377	*Epixanthus dentatus* (White, 1848)	5	14	3	*Epixanthus dilatatus* de Man, 1879; *Panopeus acutidens* Haswell, 1881; *Panopeus dentatus* White, 1848.
378	*Epixanthus frontalis* (H. Milne Edwards, 1834)	6	25	2	*Epixanthus kotschii* Heller, 1861; *Ozius frontalis* H.Milne Edwards, 1834.
Dorippidae (4 spp.)		1–7	3–18	1–5	
379	*Dorippe quadridens* (Fabricius, 1793)	7	18	4	*Cancer quadridens* Fabricius, 1793; *Dorippe atropos* Lamarck, 1818; *Dorippe nodosa* Desmarest, 1817; *Dorippe rissoana* Desmarest, 1817.
380	*Dorippoides facchino* (Herbst, 1785)	5	11	5	*Cancer facchino* Herbst, 1785; *Dorippe astuta* Fabricius, 1798; *Dorippe facchino* (Herbst, 1785) ; *Dorippe facchino alcocki* Nobili, 1903; *Dorippe sima* H. Milne Edwards, 1837.
381	*Neodorippe callida* (Fabricius, 1798)	3	9	1	*Dorippe callida* Fabricius, 1798.
382	*Nobilum histrio* (Nobili, 1903)	1	3	1	*Dorippe histrio* Nobili, 1903.
Xenophthalmidae (1 spp.)					
383	*Xenophthalmus pinnotheroides* White, 1846	4	4	0	-
Limulidae (2 spp.)		3–4	7–8	1–8	
384	*Tachypleus gigas* (O. F. Müller, 1785)	4	8	8	*Limulus gigas* O.F. Müller, 1785 ; *Limulus heterodactylus* Latreille, 1802; *Limulus latreilli* Leach, 1819; *Limulus macleaii* Leach, 1819; *Limulus moluccanus* Latreille, 1802; *Limulus viriscens* Latreille, 1806 ; *Tachypleus heterodactylus* (Latreille, 1802); *Tachypleus hoeveni* Pocock, 1902.
385	*Carcinoscorpius rotundicauda* (Latreille, 1802)	3	7	1	*Limulus rotundicauda* Latreille, 1802 (Basionym).

Table 1 continued

No.	Name of Crab Species	No. of Sub-regions	No. of Countries	No. of Synonyms	Synonyms
Dromiidae (2 spp.)		5–6	12–14	1–2	
386	*Conchoecetes artificiosus* (Fabricius, 1798)	6	14	2	*Conchoeodromia alcocki* Chopra, 1934; *Dromia artificiosus* Fabricius, 1798.
387	*Lauridromia dehaani* (Rathbun, 1923)	5	12	1	*Dromia dehaani* Rathbun, 1923 (basionym).
Raninidae (2 spp.)		4–7	7–18	0–3	
388	*Notopus dorsipes* (Linnaeus, 1758)	7	18	3	*Cancer dorsipes* Linnaeus, 1758; *Dorippe dorsipes* (Linnaeus, 1758); *Ranilia dorsipes* (Linnaeus, 1758).
389	*Raninoides personatus* Henderson, 1888	4	7	0	-

The second largest crab group in mangroves is Ocypodidae, which are detritivors or deposit-feeders. The fiddler crabs and Uca species ingest about 500 g of soil per square metre per day and they are abundant at 70 per square metre in many Southeast Asian mangroves [21]. The fiddlers hide themselves in burrows to avoid submergence from high spring tides or floods and also to protect themselves from predation. Moreover, Uca species tolerate a broad range of temperatures across their geographical distribution and hence, they are abundant in open mudflats or open canopy areas [25].

The third largest group in mangroves is Portunidae. The Portunid genus Scylla is typically associated with mangroves, commonly occurring throughout tropical to warm temperate areas of the West Pacific and Indian Oceans, for the reason that the genus especially Scylla serrata is highly tolerant to warm and increasing temperatures. Most of the brachyuran crabs especially the Portunid genus Scylla complete their larval development in the open sea and return to mangroves or estuaries at the megalopal stage for settlement and recruitment to adult populations [26].

4. Conclusions

There are a total of 389 brachyuran crab species belonging to 188 genera and 38 families in mangrove forests, located across 122 countries/territories in 10 sub-regions of the world. The crabs are highly diverse in the Indo-West Pacific (IWP) as compared to the Atlantic East Pacific hemisphere (AEP). They exceed 100 species in nine countries of the IWP viz., Indonesia, India, Japan, Thailand, Australia, Singapore, Philippines, Malaysia, and China. Four countries/territories do not have any record of crabs, which requires undertaking a survey and inventorisation. There are 55 crab species of restricted occurrence, which deserve attention to find out its IUCN conservation status. Sesarmidae is the predominant family of mangrove crabs, followed by Ocypodidae and Portunidae. The present work has brought out as many as 818 synonym names, which otherwise interfere with the preparation of a checklist for the exact number of mangrove crab species in different countries. It is a matter of necessity to conserve crabs, which are the keystone species of the mangrove habitats.

Authors Contributions

Data & literature collection, analysis & writing—original draft preparation, W.W.M; supervision, discussion, final draft preparation K.K; Both authors have read and agreed to the published version of the manuscript.

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Conflict of Interests

The authors do not have any conflict of interest.

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REVIEW ARTICLE

Research on Publication Trends for Asset Management of Offshore Facilities Between 1992 to 2022 Using Scientometric Analysis

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Abstract: The demand for monitoring activities has been more evident recently in oil and gas "O & G" activities such as exploration, drilling, production, logistics, or shipping. Consequently, these offshore infrastructures require asset management (or facilities management). This study seeks to understand the research pattern of publications within the domain of asset management in offshore infrastructures with the aim of determining the present state of the field's research. The paper conducts a scientometric analysis of publications that focus on offshore infrastructures' asset management published between 1992 and 2022. The employed search query yielded a total of 346 journal articles from the Scopus database and 43 from the Web of Science (WoS) database, respectively. The data analysis of the scientometric investigation explored research authorship, co-occurrence of keywords, number of publications, network mapping, country geographical breakdown, and literature coupling. The paper shows rising interest in monitoring and asset management in the oil and gas industry. It was concluded that the management of these infrastructures requires frequent review with the application of sustainable asset management strategies.

Keywords: Asset Management; Facilities Management; Oil and Gas; Offshore Facility; Scientometric; Bibliometric

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1. Introduction

Every firm tries to ensure that its assets are well-managed and safe for the workers to use. Thus, asset management (AM) has been a useful tool deployed by various firms. Over time, asset management has changed from simple time-based inspections of vital equipment to reliability-centered and risk management systems for all safety-critical elements (SCE), with a focus on the crucial factors and processes for calculating the life extensions of an ageing offshore structure [1–8]. According to the ISO 55000 standard, asset management is "the coordinated action of an organisation to realise value from assets" [9]. Having an asset inventory, maintenance, infrastructural design, and replacement costs and spare-parts inventory with the costs to the oil and gas (O & G) industry is still a challenge regarding various resources required. These resources include finances, time, and personnel throughout its life cycle, which is a persistent issue for facility managers and asset integrity managers in the business [10–14]. In addition to the cost consequences of sustaining these assets, extending their lives, and monitoring them, these concerns also entail developing new platforms that can produce future oil and gas supplies. As demonstrated by various breakthroughs in the sector, asset integrity management includes many components that are essential to the maintenance, serviceability and long-term viability of offshore assets [14–21].

Asset management also applies to the financial sector for the monitoring of financial assets and investment portfolios to ensure that the assets are well monitored. Amaechi et al. [22] proposed some guidelines for the asset management of offshore facilities. Using bibliometric analysis to map the literature on asset management, De Filippo et al. [23] identified 2,449 publications from management, optimization, maintenance, infrastructure, business, and finance research. The analysis techniques are related to previous scientific research that has been carried out, like those on energy efficiency [23–30]. However, taken as its whole, the offshore sector typically includes a variety of activities, such as transportation, logistics, planning for wind farms, facility maintenance, exploration, drilling, and production [30–32]. The demand for monitoring activities has been more evident recently in the construction sector, services sector, financial sector as well as the energy sector. In the latter, it is seen in various oil and gas "O & G" activities such as exploration, drilling, production, logistics, or shipping. This implies that these offshore infrastructures require asset management (or facilities management).

Following the need to meet the sustainable development goals (SDGs) of the United Nations (UN), there is a need to understand the research impact of sustainable marine structures, such as boats and buildings. The use of sustainable building materials that can withstand hard temperatures, high sea depths, unfavourable weather, powerful winds, and high significant wave heights are some of these issues. As a result, a greater understanding of the core variables, hot topics in research, and asset management procedures is needed, as covered in this investigation. This paper considers the publication records for the past three decades, from 1992 to 2022. The structure of the paper is as follows: the first section is the introduction, while the second section gives the materials and methods. The third section gives the results and analysis while the conclusions are given in the fourth section.

2. Materials and Methods

The materials and methods employed to achieve the research goals are presented in this section.

2.1 Data Collection

This study relies on data collection from accessible literature in order to perform a scientometric analysis. This established method for gathering data for this type of method was used in this study. The research approach for selecting useful articles that will be included in the data analysis was deemed important because diverse studies on asset management have covered a variety of technologies used. The data employed in this study was obtained based on criteria, including (a) contemporary and relevance: all works published between 1992 and 2022 were searched, and manually screened using keywords and abstracts; (b) peer-reviewed articles: They were included due to the rigour and reviews to remove mistakes, inaccuracies and errors, (c) the use of a research framework to ensure quality assurance. The database selection was essential for the review of the literature. It was ideal to select the database to acquire the data because of its broad coverage of journal publications and knowledge domain comparison. Operators and wildcards were used in the search. The wildcard character * was used to collect all keyword variations. Based on the purpose of the study, the keywords for the search query were (asset AND management AND of AND offshore AND facilities), ("asset management*" OR "offshore*" AND ("facilities*"). The database yielded all the articles on asset management of offshore structures that were searchable by terms found in a publication's title, abstract, or keywords. The 1992–2022 search frame was chosen to capture the ongoing expansion of asset management of offshore structures. Non-English journals were excluded from the articles considered for the data analysis in this study.

2.2 Research Methodology

In order to analyse research patterns from this field, a scientometric analysis is conducted in this study employing a research database and visualization-mapping tools. Scientometrics as employed in this study aimed to disclose the research effect of publications, researchers, journals, and research organisations in a certain field of study. This can be conducted using data-mining tools and analysis software called VosViewer [22]. Most scientometric investigations in humanities, built environment, sciences, and social sciences utilise scientific citations to provide a deeper understanding of authorship, citations, scientific relevance, and research engagement [22–30]. The current study undertakes a scientometric analysis and evaluation of the research trends by using publications relevant to the asset management of offshore facilities. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach includes details on the PRISMA 2020 statement and the PRISMA checklist. The data were synthesized and verified to align with the content of the search query.

Using the streamlined approach helps the investigator acquire a complete grasp of the development of this research topic from 1992 to 2022. To qualitatively validate the bibliometric studies, the methodology was contrasted with some recent bibliometric research cutting across different fields. The application of sampling, visualization, cluster investigation and correlation are newer methods of data analysis that have practical applications for scientometric studies in multidisciplines [22–30], ranging from the built environment to marine structures and data analysis. On the basis of the results of this scientometrics study, a thorough systematic review is then provided to provide deeper insights into the technology and applications of asset management of offshore facilities. The flowchart of the research search criteria used is presented in Figure 1.

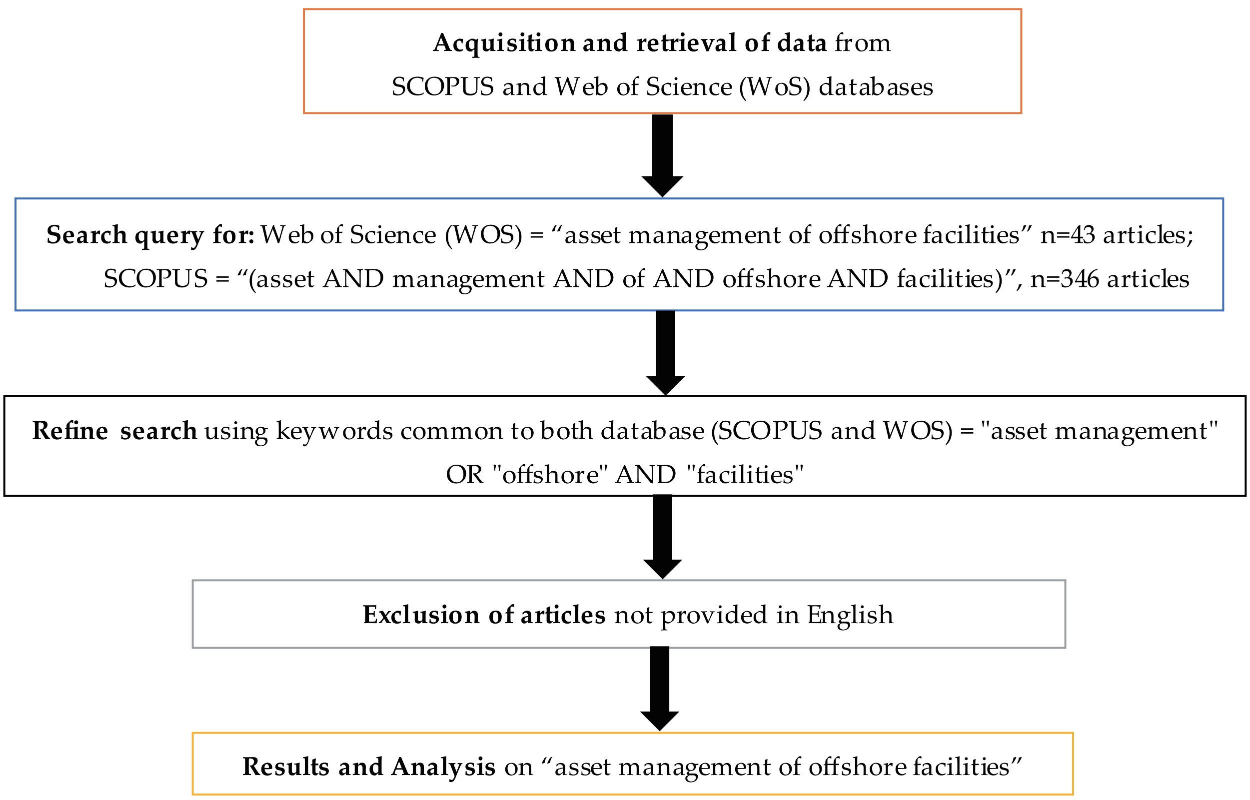

Figure 1. Research methodology on the scientometric review.

3. Results and Analysis

This section presents the results and analysis from the scientometric review.

3.1 Publication Years

The impact of the research, which can be broken down by using the publication years for the topic "asset management of offshore facilities" is the initial aspect of the results for the component meta-analysis. Figure 3 illustrates data from the Scopus database that was gathered in the middle of 2022. When the most recent publications were taken into account, the publishing output from 1992–2022 exhibited a small trend shift. From 1999, there was a more steady increase in the publication rate. In 2004, there was an increase in the publications on asset management of offshore facilities from 4 publications to 11 publications, which is related to the offshore developments that occurred in that year. The output increased from 16 publications in 2013 to 24 publications in 2014 then reduced slightly to 18 publications in 2014 before it increased steeply to 34 publications in 2015, which was the highest recorded publication on the subject area under consideration. Then it reduced to 33 publications in 2016, then reduced further to 25 publications in 2017, which is likely due to the global fall in oil prices from 2016–2017. It then increased slightly to 29 publications in 2018 then it reduced to 23 publications in 2019, but it increased to 25 publications in 2020. However, there was the global COVID-19 pandemic from 2020–2021 (which was due to the prevalence of Coronavirus), and most of the publications that are usually presented in conferences like OTC and ASME conferences were cancelled. This affected publication output in the oil and gas industry, particularly on offshore facilities. Some of the conferences had to reschedule conferences for 2021/2022 and while a few had to adapt to virtual conference presentations. In 2021, it rose to 29 publications and in 2022, it further rose to 32 publications, as that covers the selected timeline for the research. This reflects the increasing research in this subject area.

Despite these actions, the publication rate decreased from 25 publications in 2020 to 14 publications in 2021 and then 3 publications in mid-2022. Some of the technical conferences held around mid-2022, like the OTC conference that was held in May 2022 and the ASME OMAE was held in June 2022, would have not yet published their journal papers. A similar trend is observed for studies that are extracted for mid-year, however it is estimated that the publication rate at the end of 2020 would increase up to 20, due to recent developments in offshore facilities. Examples are the development of deepwater platforms by different operators like Shell, BP and Norwind Offshore. These include the conversion of new assets and contracts signed on asset management of offshore facilities. From this research, it can be observed that the research on this subject area is a function of economic activity as there were also 8 publications published in 2008 and 2009, which was also a period of a global financial crisis called economic recession. This data shows an overall growing trend in 2009 from 8 publications to 16 publications in 2010 which shows some increased stability in the O & G industry. Importantly, the trend that rose in 2013 coincided with some key developments in the asset management of offshore facilities, which include platform commissioning. This study shows that the number of publications increased at a normal rate but had a pattern of slowly increasing between 1993 and 2021.

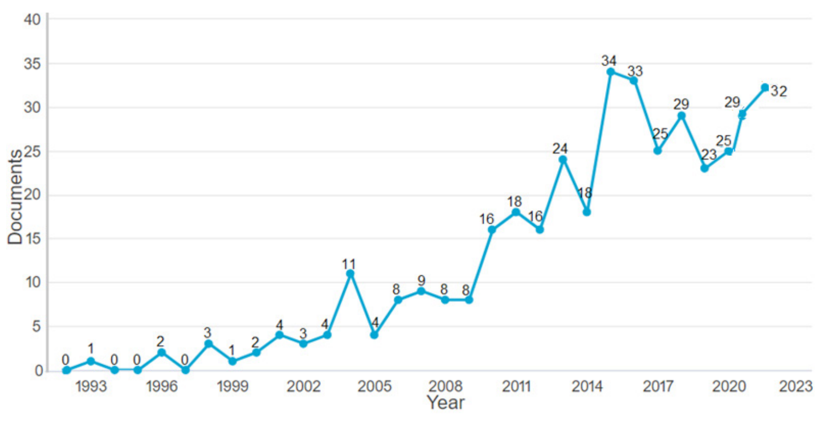

Figure 2. The number of publication records versus publication years.

Source: Scopus Database.

3.2 Publication Authors

Based on the authorship of published works, the analysis of research trends on asset management of offshore facilities includes another component. Determining the research trends from the authors helps to understand the developments made and future research trends in the subject area. A scientometric investigation reveals the impact of authors' records on the subject area, and their publication records provide important insights into the research. Using the data retrieved from the Scopus database, as seen in Table 1, the highest publications by authors were published by Boutrot, J., having 5 publications, followed by Nezamina, A., and Rossi, R., as each had 4 publications. The next author grouping was the authors that had 2 publications, which were: Adeyemi, O.S., Andersen, E.S., Barrios, A., Berger, P.E., Biniwale, S., Briers, J., Ciaraldi, S.W., Gallagher, D., and Hillier, E. Another group of authors, including Ajayi, A., and Akinyemi, O., also had 2 publications each. The study found that the largest group of authors in this subject area were those with a single publication.

The component for the authors is considered the penultimate component in the meta-analysis because it is the authors that carry out the research, analyze the result findings, discuss the results, report them and publish them. The scientific literature on asset management of offshore facilities has been influenced by various researchers. The authorship contributions for asset management of offshore facilities displayed in Figure 4 do not represent the exhaustive list of authors in the field of over 300 authors. The 15 authors are the most published, as obtained from the publication database using the search query in Scopus. The collection of documents has over 200 authors, a number of whom have just 1 publication. Table 1 presents the top 17 authors with their h-index, the number of publications and the citations. The h-index of some of the authors was low despite having a high publication record due to a lack of citations or low citations. Citations show the relevance or significance of the publication on the specialization. While the publication record of the authors may be high, it is also important that these publications get cited and references by other authors, publishers, presenters and publishers. From the record in Table 1, the highest citations were 898, by Amaechi, C.V. with a h-index of 20, followed by 153 citations, by Briers, Jan with a h-index of 5. Conversely, the author with the highest number of publications was Ciaraldi, Stephen W., with 67 documents and a h-index of 4. This showed that the authors' works are relevant based on the fairly high citations received in the publications for asset management of offshore facilities.

Table 1. List of top 17 authors on "asset management of offshore facilities" research with h-index, publication amount and citations.

Authors	h-index	Publications	Citations
Boutrot, Jonathan	1	8	4
Nezamian, Abe	5	20	54
Rossi, Roberto	4	14	78
Adeyemi, Temitope	2	3	25
Andersen, Erlend Stokstad	3	3	14
Barrios, Andre	0	3	0
Berger, Per Erik	0	3	0
Biniwale, Shripad Suhas	6	30	102
Briers, Jan	5	18	153
Ciaraldi, Stephen William	4	67	28
Gallagher, Daniel	1	7	2
Hillier, Elizabeth	3	5	14
Hopkins, Peter	0	3	0
Legrégeois, Nicolas	1	7	2
Amaechi, Chiemela Victor	20	54	898
Ajayi, Ayodele Abraham	1	3	1
Akinyemi, Olusegun Peter	5	7	80

Source: Scopus Database.

3.3 Publication Subjects

The literature search utilizing published subjects is another focus of the publication trend examination in this paper, as shown in Figures 3 and 4. They represent the categorization of publications on 'asset management of offshore facilities' based on their respective topic matter. In the 2022 data, Energy constituted the largest share (37.6%) at 219 publications, followed by Engineering disciplines (27.1%) at 136 publications, which together accounted for almost a quarter. Then, it was followed by Earth and Planetary Sciences (21.0%) at 122 publications, then it was followed by Chemical Engineering (3.6%) at 21 publications, then it was followed by Materials Sciences (3.4%) at 20 publications. Then, it was followed by Environmental Sciences (2.9%) at 17 publications, then it was followed by Social Sciences (1.4%) at 8 publications. Next was Physics and Astronomy (1.2%) at 7 publications, and Chemistry (1.2%) at 6 publications. Also, it showed that Mathematics (1.0%) scored the lowest at 6 publications, while Others, comprising small subgroups, accounted for 3.4%, demonstrating that there were additional, emerging fields working on asset management of offshore facilities.

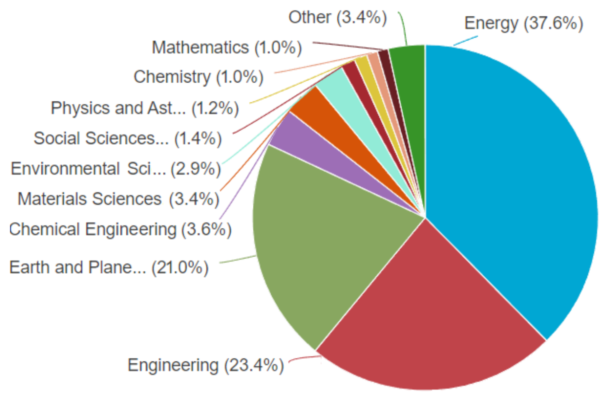

Figure 3. Classifying publications using subjects for 'asset management of offshore facilities'.

Source: Scopus.

Similarly, we found comparable patterns from the second database called Web of Science data in other relevant domains as shown in Table 2 and the visualizations in Figure 4. According to the visualisation treemap used to display all publications on asset management of offshore facilities, there were 10 publications on Marine Engineering, 7 publications on Ocean Engineering, 6 publications on Energy Fuels, 6 publications on Civil Engineering, 6 publications on Mechanical Engineering, 6 publications on Petroleum Engineering, 5 publications on Industrial Engineering, 4 publications on Chemical Engineering, 4 publications on Oceanography and 4 publications on Engineering Multidisciplinary. A detailed breakdown of the various engineering disciplines, such as Civil Engineering, Mechanical Engineering, and Engineering Multidisciplinary, was also conducted using the tabular data in Table 2. This further illustrates how asset management of offshore facilities, cuts across various facets, such as the drilling, production, transportation, refinery and chemical assets as well as the production lines used for the marine risers and pipelines. This study also shows the importance of asset management to ensure that new and existing systems such as machine parts, are well maintained using state-of-the-art management systems, sustainable maintenance models and the best expertise for the deployment. It also shows that institutions, companies, training agencies and consultancy firms are invested in this field and their research outputs have influenced interest in engineering courses.

3.4 Publication Type

The scientometric review conducted in this section focuses on the literature search using publication type for asset management of offshore facilities. Figure 5 illustrates the focus of the meta-analysis of the scientometric review considering literature search as per publication type. These sectors in Figure 5 stand for the type-based classification of articles for asset management of offshore facilities. It was found that conference papers come in first at 85.5% with 296 publications, followed by journal papers (or articles) which are second at 9.2% with 32 publications. The next sectors include the conference reviews which were 6 documents at a rate of 1.7%, followed by book chapters at 4 documents at a rate of 1.2%, and notes were 4 publications at the rate of 1.2%. Review papers followed, producing 3 documents at a rate of 0.9%, while books were the least as 1 book was recorded at 1 publication at the rate of 0.3%. The output of the other types, which included data papers, method papers, editorial papers, erratum papers, letter papers, and publication data, were not recorded. This suggests that the volume of published outputs, which are primarily research articles, represent the research classes (classifying the types using details) for asset management of offshore facilities.

Figure 4. Treemap Visualization showing various areas for 'asset management of offshore facilities'.

Table 2. Data on publication subjects for 'asset management of offshore facilities'.

Web of Science Categories	Record Count	% of 43	Web of Science Categories	Record Count	% of 43
Engineering marine	10	23.26%	Environmental sciences	2	4.65%
Engineering ocean	7	16.28%	Green sustainable science technology	2	4.65%
Energy fuels	6	13.95%	Management	2	4.65%
Engineering civil	6	13.95%	Computer science information systems	1	2.33%
Engineering mechanical	6	13.95%	Construction building technology	1	2.33%
Engineering petroleum	6	13.95%	Ecology	1	2.33%
Engineering industrial	5	11.63%	Engineering environmental	1	2.33%
Engineering chemical	4	9.30%	Engineering manufacturing	1	2.33%
Engineering multidisciplinary	4	9.30%	Environmental studies	1	2.33%
Oceanography	4	9.30%	Geochemistry geophysics	1	2.33%
Engineering electrical electronic	3	6.98%	Geosciences multidisciplinary	1	2.33%
Operations research management science	3	6.98%	Materials science composites	1	2.33%
Economics	2	4.65%			

Source: WoS Database.

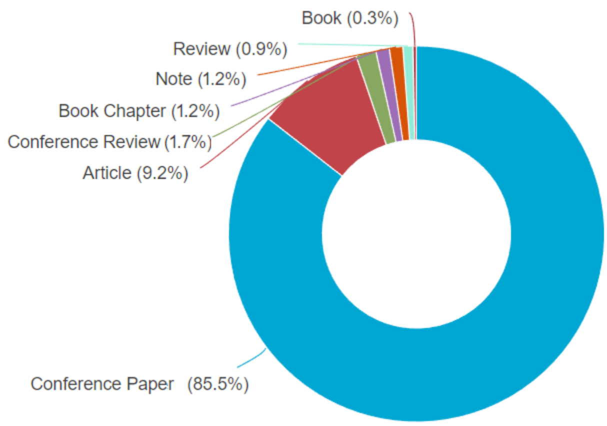

Figure 5. Classifying types of publications for 'asset management of offshore facilities'.

Source: Scopus database.

3.5 Publication Sources

The current meta-analysis focuses on the publishing sources by using two academic databases —Scopus and WoS Core Collection. To confirm the existence of the publications, the h-index of the publications was looked up to confirm the data from the Scimango database. Aside from these choices made, it is important to state that other existing prominent academic databases like PubMed, Science Direct, DOAJ, Engineering Village, etc. could also be utilised in similar studies. It was feasible to draw further conclusions about the examination of asset management of offshore facilities. This was conducted by a thorough, scientific and techno-literary method using scholarly papers from conferences and journals. Also considered were academic publishers with databases and repositories, like Sage, Springer Link, Taylor & Francis, and Elsevier. Specialist journals like Ocean Engineering, which has a high h-index of 109 and an impact factor of 3.7985, Marine Structures, which has a high h-index of 71 and also an IF (impact factor) value of 4.52, and international conferences like ASME OMAE, ASCE, SPE, OTC, ISOPE, etc., were also taken into consideration as publications with high significance. From Table 3, it was observed that the majority of publications on asset management of offshore facilities were presented as journal papers from the proceedings of three significant conferences—OTC, SPE, ASME OMAE. The top journals on asset management of offshore facilities were then screened to be included in the final product. In Table 4, the journals that appeared the most frequently were Elsevier's Ocean Engineering, Elsevier' Marine Structures, MDPI's Journal of Marine Science and Engineering, etc. These articles, though, were fewer in number than the ones that appeared in associated Q1 periodicals. The details of this subsequent analysis revealed that the Offshore Engineer journal published the highest volume of publications that are journal articles, though it has a low h-index of 4. However, other journals have 1 publication, based on the subject area, but high h-index, such as Renewable Sustainable Energy Reviews with an h-index of 337, Journal Of Hazardous Materials with an h-index of 307, Chemical Engineering Journal with an h-index of 228 and Reliability Engineering and Systems Safety with an h-index of 157. This study also showed that the highest publications were conference papers from Proceedings of the annual Offshore Technology Conference (OTC), with an h-index of 44 and had 41 publications, spread over many years, as seen in Table 3. The second highest publications were conference papers from Proceedings of the Society of Petroleum Engineers (SPE) Annual Technical Conference And Exhibition, with an h-index of 85 and 21 publications. The third highest publications were 10 publications from Proceedings Of The International Conference On Ocean, Offshore Mechanics And Arctic Engineering (OMAE), with a h-index of 10. Further review of these publication lists showed that comparable areas investigated by researchers studying asset management on offshore facilities, ranging from reliability to management systems. Secondly, the early increased improvements in asset management on offshore facilities, which were observed as early as in 1993, led to the publication of numerous patents between 1992 and 2022 by various inventors. Despite the developments in the offshore industry, the publication sources are still found to be presented in these top technical conferences, and also more recent studies include management systems, and certifications, life cycle, asset management and reliability studies.

Table 3. Publications on top conference proceedings for asset management of offshore facilities.

Source Title	Publications	% of 103	H-index	Database
Proceedings Of The Annual Offshore Technology Conference OTC	41	39.806	44	WoS
Proceedings SPE Annual Technical Conference And Exhibition	21	20.388	85	WoS
Proceedings Of The International Conference On Ocean, Offshore Mechanics And Arctic Engineering OMAE	10	9.709	47	Both
NACE International Corrosion Conference Series	4	3.883	40	WoS
Proceedings Of The International Offshore And Polar Engineering Conference	4	3.883	49	Both
SPE Asia Pacific Oil And Gas Conference	2	1.942	25	WoS
SPE Hydrocarbon Economics And Evaluation Symposium	2	1.942	14	WoS
International Conference On Renewable Energy Research And Applications ICRERA	2	1.942	18	Scopus
Proceedings Of The IADC SPE Asia Pacific Drilling Technology Conference	1	0.971	22	WoS
Proceedings Of The Institution Of Civil Engineers: Forensic Engineering	1	0.971	12	WoS
SPE International Symposium On Oilfield Chemistry Proceedings	1	0.971	37	WoS
Proceedings SPE Symposium On Improved Oil Recovery	1	0.971	50	WoS
Proceedings Annual Convention Gas Processors Association	1	0.971	13	WoS
Proceedings Of The European Petroleum Conference	1	0.971	24	WoS
Safety Reliability And Risk Analysis Theory Methods And Applications	1	0.971	8	Scopus
NAV International Conference on Ship & Shipping Research	1	0.971	5	Scopus
Proceedings of International Business Information Management Association Conference IBIMA	1	0.971	5	Scopus
Proceedings Of The International Conference On Quality Reliability ICQR	1	0.971	3	Scopus
Proceedings Of The Institution Of Mechanical Engineers Part E Journal Of Process Mechanical Engineering	1	0.971	34	Both
Symposium On Loss Prevention And Safety Promotion In The Process Industries	1	0.971	3	Scopus
Annual Reliability And Maintainability Symposium RAMS	2	1.942	44	Both
Advances In Production Management Systems APMS	1	0.971	6	Scopus
International Conference On Health Safety And Environment In Oil And Gas Exploration And Production	2	1.942	14	WoS

Source: Scopus and WoS Databases.

Table 4. Publications on top journals for asset management of offshore facilities using Scopus and WoS Databases.

Source Title	Publications	% of 55	H-Index	Database
Offshore Engineer	3	5.455	4	WoS
Chemical Engineering Transactions	2	3.636	39	Both
Journal Of Marine Engineering And Technology	2	3.636	17	Both
Journal Of Offshore Technology	2	3.636	4	WoS
Journal Of Quality In Maintenance Engineering	2	3.636	59	WoS
Oil And Gas Journal	2	3.636	36	WoS
IFIP Advances In Information And Communication Technology	2	3.636	56	Both
Reliability Engineering And System Safety	1	1.818	157	Both
SPE Production And Operations	1	1.818	56	Both
Journal of Petroleum Technology JPT	2	3.636	36	Scopus
International Journal Of Energy Sector Management	1	1.818	24	Scopus
International Journal Of Oil Gas And Coal Technology	1	1.818	19	Scopus
ABB Review	1	1.818	18	WoS
ASCE ASME Journal Of Risk And Uncertainty In Engineering Systems Part B Mechanical Engineering	1	1.818	14	Both
American Society Of Mechanical Engineers Pressure Vessels And Piping Division Publication PVP	1	1.818	30	WoS
Atmosphere	1	1.818	46	Both
Automation In Construction	1	1.818	138	Both
Chemical Engineering Journal	1	1.818	248	WoS
Global Pipeline Monthly	1	1.818	4	WoS
Hydrocarbon Engineering	1	1.818	12	WoS
Hydrocarbon Processing	1	1.818	28	WoS
Journal of Offshore Mechanics And Arctic Engineering, ASME	1	1.818	49	Both
International Journal Of Automation And Computing	1	1.818	41	WoS
International Journal Of Energy Production And Management	1	1.818	8	WoS
International Journal Of Technology And Human Interaction	1	1.818	20	WoS
Journal Of Hazardous Materials	1	1.818	307	WoS
Journal of Loss Prevention In The Process Industries	1	1.818	88	Both
Malaysian Construction Research Journal	1	1.818	11	WoS
Ocean Engineering	1	1.818	109	Scopus
Marine Structures	1	1.818	71	Both
Applied Ocean Research	1	1.818	74	Scopus
Mathematical Problems In Engineering	1	1.818	68	Both
Neftyanoe Khozyaystvo - Oil Industry	1	1.818	18	WoS
Offshore	1	1.818	11	WoS
Oil Gas European Magazine	1	1.818	17	WoS
Petrophysics	1	1.818	37	Both
Ocean Coastal Management	1	1.818	90	Scopus
Journal of Marine Science and Engineering JMSE	1	1.818	29	Scopus
Journal of Quality In Maintenance Engineering	1	1.818	59	Scopus
Renewable Sustainable Energy Reviews	1	1.818	337	Scopus
Materials Performance	1	1.818	26	WoS
Built Environment Project and Asset Management	1	1.818	24	Scopus
Ecological Economics	1	1.818	220	Scopus
European Journal Of Industrial Engineering	1	1.818	28	Scopus
IEEE access	1	1.818	158	Scopus
IET Renewable Power Generation	1	1.818	84	Scopus

3.6 Publication Affiliation by Oil Companies

The scientometric analysis of publications was conducted on the research contributions by oil companies for asset management of offshore facilities. From the data in Figure 6, the highest contributor in this subject area was found to be Schlumberger having supported 21 publications, followed by Petronas having supported 18 documents. Royal Dutch Shell has supported 12 publications, while Det Norske Veritas & Germanischer Lloyd (DNVGL) has supported 10 publications. Both Chevron and Eni have supported 8 publications each, while Halliburton has supported 7 publications. Bureau Veritas (BV) has supported 6 publications while total has supported 4 publications. Both Saudi Arabian Oil Company and Equinor have supported 4 publications each while Exxon Mobil, BP, Petronas and Abu Dhabi National Oil Company also each have supported 3 publications on the subject area. It should be noted that the extent of the support, based on financial contributions, grant support and project funding was not included in the data obtained from the SCOPUS database. This study indicates that the oil companies are highly invested in training, knowledge and education on asset management of oil companies, as these companies aim to ensure that their offshore assets are well-maintained.

3.7 Publication Affiliation by Universities

The bibliometric analysis results of publications related to the subject area are crucial in understanding the impact of institutions or organisations, referred to as affiliations, on research. Examining the results of bibliometric studies conducted on publications related to the topic is necessary to gain an understanding of the affiliations, which are the entities that influence the research. It is essential to comprehend the support given by different affiliations to asset management of offshore facilities to perform an analysis of the research effect that was produced by the organisation or institution. this is presented as a breakdown of publication volume produced by various departments. Consequently, the databases yielded results that included papers from a variety of disciplines. Many research organisations, universities, polytechnics, and private companies are currently making contributions to the body of scholarly work compiled on asset management. The scientometric analysis on publications was conducted on the research contributions by higher education academy (or higher institutions) for asset management of offshore facilities. As observed in Figure 7, the document count for twelve (12) top institutions in the subject area showed that the University of Stavanger with 7 publications in WoS and 6 publications in Scopus. This was followed by Universiti Teknologi Petronas with 1 publication in WoS and 3 publications in Scopus, followed by VIA University College with 1 publication in WoS and 3 publications in Scopus. Other universities with 2 publications in this subject area include Cranfield University, University of Adelaide, University of Kent, Tianjin University and University of Bologna. Several other universities have recorded 1 publication in this field, such as China Uni-

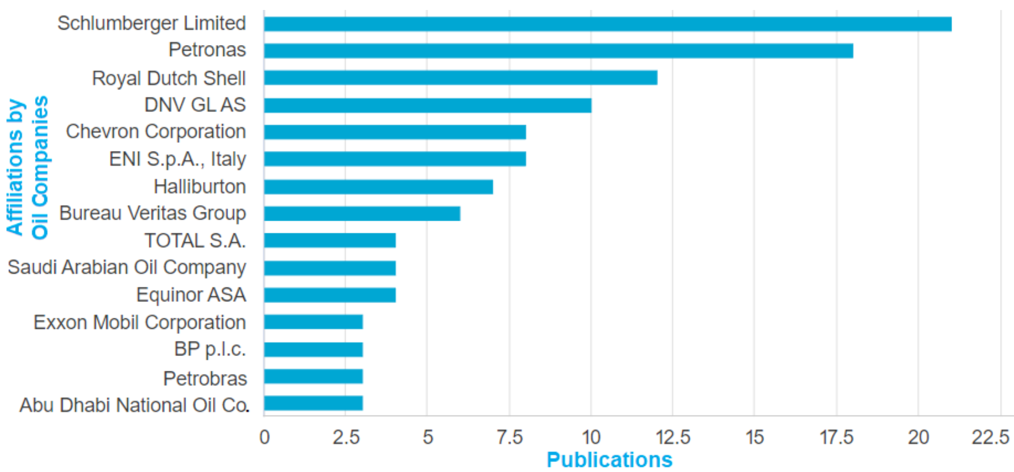

Figure 6. Literature search distribution on the research contributions on affiliation by oil companies for 'asset management of offshore facilities'.

Source: Scopus Database.

versity of Geosciences, China University of Petroleum, and Astrakhan State Technical University. It was noted that various universities are invested in this research area, due to the need to find solutions on asset management in the offshore industry as well as the oil and gas industry in general. It was also noticed that most of these institutions offer courses related to petroleum engineering, subsea engineering, project management, asset management, construction management and naval architecture, thereby promoting sustainable research and education in this area. However, there is the need for more institutions to develop a research interest in this area, and apply cutting-edge systems, which will require collaboration between the industry and academia. A detailed list of affiliations on asset management of offshore facilities is provided in Table 5.

Table 5. List of affiliation by universities for research and publications on 'asset management of offshore facilities'.

Affiliations	Record Count	% of 43	Affiliations	Record Count	% of 43
Universitetet i Stavanger (University of Stavanger)	7	16.279	Natl Tech Univ Athens (NTUA)	1	2.326
Cranfield University	2	4.651	Petrobras R D Cenpes	1	2.326
Delft University of Technology	2	4.651	Reg Maritime Univ	1	2.326
Memorial University Newfoundland	2	4.651	Rzeszow University of Technology	1	2.326
University Of Kent	2	4.651	Southwest Petroleum University	1	2.326
University Of Western Australia	2	4.651	Tianjin university	1	2.326
Astrakhan State Technical University	1	2.326	Udice French Research Universities	1	2.326
Centre National De La Recherche Scientifique (CNRS)	1	2.326	Ulsan National Institute Of Science Technology UNIST	1	2.326
The University Of Adelaide	1	2.326	United States Department Of Defense	1	2.326
China University of Geosciences	1	2.326	United States Navy	1	2.326
China University of Petroleum	1	2.326	Univ Piraeus UNIPI	1	2.326
Cnrs institute of ecology environment inee	1	2.326	Universite de Bretagne Occidentale	1	2.326
Coastal Research and Planning Institute (CORPI)	1	2.326	Universite Paris Saclay	1	2.326
Dalian university of technology	1	2.326	University of Bologna	1	2.326
Ecole des Ponts Paristech	1	2.326	University of Edinburgh	1	2.326
Embry Riddle Aeronautical University	1	2.326	University of Maryland College Park	1	2.326
European Academy OF Bozen Bolzano	1	2.326	University of Sevilla	1	2.326
Heriot Watt University	1	2.326	University of Strathclyde	1	2.326
Hohai University	1	2.326	University of Tun Hussein Onn Malaysia	1	2.326
IFREMER	1	2.326	University System OF Maryland	1	2.326
Institut National de la Recherche Agronomique (INRAE)	1	2.326	VIA University College	1	2.326
Istanbul Technical University	1	2.326	Xi'an University of Architecture and Technology	1	2.326
Klaipeda University	1	2.326	Yokohama national university	1	2.326
Multimedia University	1	2.326			

Source: Scopus and WoS databases.

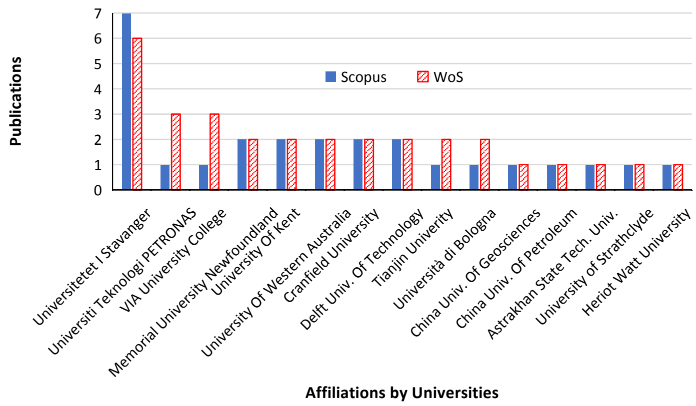

Figure 7. Literature search distribution on the top research contributions on affiliation by universities for 'asset management of offshore facilities'.

Source: Scopus and WoS databases.

3.8 Publication Funding Agencies/Funders

The bibliometric analysis results of publications related to the subject area demonstrate that funders or funding agencies significantly increase research outputs and enhance sustainable education in higher education academies (HEA) such as universities, as well as research institutions and government organizations. One aspect of this bibliometric study involved validating certain studies by cross-referencing them with their respective funders, and grant numbers, as detailed in Tables 6 and 7. It was noted that oil companies were among the principal funders as Royal Dutch Shell and Schlumberger each funded research in the area three times. Certification also played a crucial role in the asset management of offshore facilities. Australian Research Council followed, having funded research twice, while other entities funded it once, according to the search keywords used. The findings also indicate progress in research within this domain, with a high growth potential, especially with the expansion of offshore wind farms. However, there were significant challenges in obtaining most of the grant numbers for the research works on asset management of offshore facilities. It was also noticed that these funders have helped most institutions to have a high h-index and REF (Research Excellence Framework) index. Furthermore, it was observed that the funders were from various global locations, indicating their collective support for robust asset management which will ensure sustainable drilling, production operations, and energy generation. From this investigation, the asset management certification companies identified and compared, included Det Norske Veritas Holding & Germanischer Lloyd (DNV GL), Bureau Veritas (BV), and Lloyds Registers. DNV GL had the highest research funding support, received three times the highest, followed by Lloyds Registers twice while BV received it once. Additionally, Table 7 shows that the grant number with the highest contribution in this research area is Ih140100012. It should be noted that 27 records (62.791%) from the funders list and 35 records (81.395%) from the grant numbers' list based on the grant data obtained from the WoS database were excluded from the study because they did not contain data in the field being analyzed.

3.9 Publication Country

The findings of this research indicated that there are varying interests seen in the publications on asset management of offshore facilities. The distribution of the publication by country on this subject area shown in Figure 8 and Table 8 shows that different countries are interested in publishing on asset management. It was observed that the publications on the subject area, according to Scopus, were mostly published in the United States of America (U.S.A.), with 116 publications, then the United Kingdom (U.K.) with 40 publications then Malaysia with 24 publications. Also, the other top countries identified include Australia, Norway, Italy, Canada, Indonesia, India, France, Saudi Arabia, China, Denmark, Nigeria and Brazil. It was identified that the country with the highest publications—the U.S.A., had more than twice the amount of publications from the country with the second highest publications (U.K), which shows the extent of research conducted, although it is also understandable because the U.S.A. has a high number of offshore assets in their inventory.

Table 6. List of funding agencies on publications and research contributions by funding agencies/funders for 'asset management of offshore facilities'.

Funding Agencies/Funders	Record Count	Database/ Source	Funding Agencies/Funders	Record Count	Database/ Source
Australian Research Council	2	WoS	Hibernia management and Development Company	1	Scopus
Abu Dhabi National Oil	1	Scopus	Inail Istituto Nazionale Per L Assicurazione Contro Gli Infortuni Sul Lavoro	1	Both
Agro Paris Tech	1	Both	Japan Society For The Promotion Of Science	1	WoS
Apply Sorco	2	WoS	Kementerian Pendidikan dan Kebudayaan	1	Scopus
The National Research Foundation Of Korea	1	WoS	Open Fund Of State Key Laboratory Of Oil And Gas Reservoir Geology And Exploitation Southwest Petroleum University	1	Both
BHP Billiton	1	Both	Ministry Of Education Culture Sports Science And Technology Japan Mext	1	WoS
BP	1	Both	Naradowa Agenja Wyminany Akademickiej	1	Scopus
Bureau Veritas (BV)	1	Both	National Key Research And Development Program	1	Both
Calce Consortium	1	WoS	National Science And Technology Major Project	1	Both
Changzhou Science And Technology Program	1	Both	Natural Science Foundation Of Jiangsu Province	1	Both
Chevron	1	Scopus	Natural Sciences And Engineering Research Council Of Canada Nserc	1	Both
China Postdoctoral Innovative Talents Support Program	1	Both	Niger Delta Development Commission (NDDC)	1	Scopus
CHINA National Petroleum Corporation	1	WoS	Net Zero Technology Centre	1	WoS
CNOOC (China National Offshore Oil Corporation)	1	WoS	O G Operator Company	1	WoS
Department For Applied Science University And Research Of The Autonomous Province Of South Tyrol Italy	1	WoS	UK Robotics And Artificial Intelligence Hub For Offshore Energy Asset Integrity Management Orca Hub	1	WoS
Direktorat Jenderal Pendidikan Tinggi	1	Scopus	Lloyds Register	2	WoS
Det Norske Veritas Holding & Germanischer Lloyd (DNV GL)	3	WoS	Polish National Agency For Academic Exchange Nawa	1	Both
Engineering Physical Sciences Research Council EPSRC	1	Both	PTTEP (PTT Exploration and Production)	2	Both
Equinor	1	WoS	Research Development Corporation Rdc Of Newfoundland And Labrador	1	Both
Exxon Mobil Corporation	1	WoS	Research Project Interreg Iva Valmer	1	Both
Fondation De France	1	WoS	Royal Dutch Shell	3	Both
H2020 European Commission Project Paris Reinforce	1	WoS	Schlumberger	3	Both
Harbor Energy	1	WoS	Scientific Research Starting Project Of Swpu	1	Both
Shell Nigeria Exploration Production Company Limited	1	Both	UK Research Innovation UKRI	1	WoS
Taqa	1	WoS	OML	1	WoS
Telekom Malaysia Research Development	1	WoS	Ulsan National Institute Of Science And Technology	1	WoS
Total Sa	1	Both	Woodside Energy	1	WoS

Source: Scopus and WoS databases.

Table 7. List of some grant numbers showing research contributions by funding agencies/funders on 'asset management of offshore facilities'.

Grant Numbers	Record Count	% of 43	Grant Numbers	Record Count	% of 43
Ih140100012	2	4.651	Bk20150249	1	2.326
1.160046.01	1	2.326	Bx20190292	1	2.326
15k12459	1	2.326	Ccl2012tjpxxs0053	1	2.326
2016zx05028-001-006	1	2.326	Cj20159053	1	2.326
2018qhz017	1	2.326	Ep/r026173/1	1	2.326
2018yfc0310201	1	2.326	Nrf-2014r1a1a1003653	1	2.326
73/40.3	1	2.326	Pln201827	1	2.326
820846	1	2.326	Tm Rnd Mmue/160021	1	2.326

Source: WoS database.

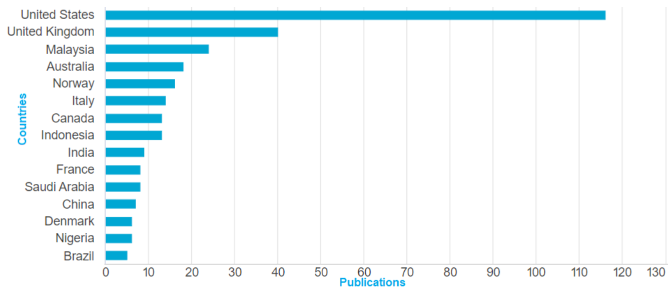

Figure 8. The top 15 countries on "asset management of offshore facilities".

Source: Scopus database.

Table 8. The research engagements by countries that are the most relevant on "asset management of offshore facilities".

Countries/Regions	WoS	Scopus	% of Scopus Sum (1998)	% of WoS Sum (1526)
USA	6	116	13.953	4.033
Norway	8	16	18.605	5.377
UK	10	40	23.256	2.688
China	4	7	9.302	2.688
Nigeria	1	6	2.326	0.672
Australia	3	18	6.977	2.017
France	3	8	6.977	2.017
Italy	3	14	6.977	2.017
Malaysia	3	24	6.977	2.017
Brazil	2	5	4.651	1.344
Canada	2	13	4.651	1.344
Netherlands	2	5	4.651	1.344
Spain	2	3	4.651	1.344
Belgium	1	4	2.326	0.672
Denmark	1	6	2.326	0.672
Ghana	1	1	2.326	0.672
Greece	1	1	2.326	0.672
Japan	1	1	2.326	0.672
Lithuania	1	1	2.326	0.672
Myanmar	1	1	2.326	0.672
Angola	1	1	2.326	0.672
Poland	1	1	2.326	0.672
Russia	1	2	2.326	0.672
South africa	1	1	2.326	0.672
South korea	1	1	2.326	0.672
Thailand	1	1	2.326	0.672

Source: Scopus and WoS databases.

3.10 Publication Keywords' Word Cloud

The findings of this research indicated that there has been an increase in publications on asset management of offshore facilities in recent times. The keywords used to generate the word cloud were sampled publications on the search query. Also, the word cloud was developed using Free Word Cloud Generator, available at: https://www.freewordcloudgenerator.com/generatewordcloud. The wordlist for the keywords "asset management of offshore facilities" can be seen in Table 9 and Figure 9. It shows that "management" is the word with the highest frequency (31), followed by "asset" with a frequency of 22, followed by "risk" with a frequency of 13, followed by "assessment" with a frequency of 8. The lowest frequency of 1 had been noticed across a range of keywords including offshore, monitoring, mapping, bibliometric, energy, risers, pipelines, flowlines, etc.

Figure 9. The word cloud for keywords on "asset management of offshore facilities".

Table 9. The wordlist for keywords on "asset management of offshore facilities".

Frequency	Word	Frequency	Word	Frequency	Word	Frequency	Word
31	management	4	sustainability	3	strategy	1	industry
22	asset	4	maintenance	3	making	1	sustainable
13	risk	4	life	3	system	1	monitoring
8	assessment	4	systems	3	iso	1	flowlines
7	corrosion	4	integrity	3	cycle	1	offshore
5	decision	4	strategic	3	performance	1	text
3	budget	2	project	2	materials	1	review
3	analysis	2	oil	2	control	1	motives
3	uncertainty	2	gas	2	support	1	barriers
2	literature	2	safety	2	reliability	1	flowline
2	physical	2	practice	1	resilience	1	downstream
2	infrastructure	2	subsurface	1	engineering	1	pipelines
1	rehabilitation	1	deterioration	1	scientometrics	1	environmental
1	real	1	bibliometric	1	analytics	1	risers
1	estate	1	mapping	1	metro	1	energy
1	property	1	optimisation	1	urban	1	railway

3.11 Publication Research Themes

The findings of this research include the identification of research themes on asset management, which also showed an increase in the research area. One observation made is that asset management could also be used to refer to facilities management, depending on the domain. However, asset management has given rise to various management techniques because it is a vital part of the oil and gas sector. It ensures adequate monitoring of these offshore facilities, considering the lifespan, life extension, serviceability, ageing, and other aspects of asset management [33–41]. The offshore sector has recently faced challenges related to a number of issues, including the structural integrity of offshore assets [42–47]. Other issues include offshore asset monitoring [48–50], asset life extension [49–52], risk assessments [53–56], Health, Safety and Environment (HSE) [57–62], sustainability indicators [63–66] and asset management [67–70]. Among the metrics applied to offshore facilities are the following: the design of an offshore platform, production activities, management system models, and the location of the oil field. Since the operational life expectancy of a significant percentage of the offshore infrastructure is currently approaching or has already passed, this particular niche has seen an increase in life extension schemes for offshore buildings and other marine structures [71]. However, various factors affect the asset management approach that will be applied as well as the metrics and indicators that will be employed to assess the offshore facility. The historical background of oil and gas exploration is also available in the literature [72–82]. The use of offshore platforms in deep water locations creates significant challenges for oil operators in the O & G sector, which should also be considered to ascertain asset life extensions [83–90]. High sea depths, severe weather, extremely windy circumstances, and high significant wave heights are some of these difficulties [91–97]. As a result, facilities management is required, which may lead to additional factors including the development, deployment, and commissioning of offshore facilities [98–103]. Based on the scope of this research, some studies were also identified that cover similar scientometric reviews in related areas. However, it is noteworthy to state the PRISMA 2020 statement was considered in this study [104–110] because it provides guidelines on scientometric analysis and shows details on the tools used in preparing the analysis.

However, the research trends are affected by various global issues and developments in the oil and gas industry. Notable trend shifts were observed during the 2016/2017 decline in oil prices and the 2020/2021 global COVID-19 pandemic, which affected work and sustainable supply chains in various industries [111–121]. The study also found related scientometric works on Sustainable Marine Structures which shows an evolving trend in the journal [122-124]. While there are studies that reflect that risk management is important as seen in the construction sector [125-127], another set of themes that is increasing in the sector involves the monitoring of assets [22,127] as this helps to satisfy the industry's needs in managing assets considering the perspective of the operators [127-130]. One key advantage of proper asset management is that it enables the decommissioning process to be achieved successfully [22,127,130].

The study also showed that there were different funders that support research on asset management of offshore facilities which shows some collaboration between industry and academia. The study also highlighted that different funders support research on asset management of offshore facilities, demonstrating some collaboration between industry and academia. Additionally, several oil companies support the research area, which is indicative of their investment in research and development. However, the successful operation of monitoring these offshore facilities using various asset management systems will enable the oil multinationals and various operators to pursue sustainable oil exploration and related operations.

4. Conclusions

In this paper, the scientometric analysis of asset management of offshore facilities is carried out based on research trends. The data used in this investigation were retrieved from Scopus and Web of Science (WoS) databases. This study presents the results for publication history, citations, publication type, publication subject categories, authorship, affiliations funders, and keyword correlations. The scientometric analysis employs state-of-the-art methods of scientific literature review to investigate the research patterns on asset management of offshore facilities. This research comprises recent scholarly articles from academic publication databases covering both journal papers and conference papers from conference proceedings.

The findings of this research show that the USA was the country that produced the highest publications on asset management of offshore facilities. It also revealed that the location for most of the technical conferences held was in the USA, such as the OTC, SPE and ASME's OMAE conferences. The results indicated that there has been an increase in publications on asset management of offshore facilities in recent times. However, the research trends are affected by various global issues and developments in the oil and gas industry. Notable trend shifts were observed during the 2016/2017 decline in oil prices and the 2020/2021 global COVID-19 pandemic, which affected work and sustainable supply chains in various industries. The study also found related scientometric works on Sustainable Marine Structures which shows an evolving trend in the journal. The study also showed that different funders support research on asset management of offshore facilities which shows some collaboration between industry and academia. The study also highlighted that different funders support research on asset management of offshore facilities, demonstrating some collaboration between industry and academia. Additionally, several oil companies support the research area, which is indicative of their investment in research and development. Successful operation of offshore facilities using various asset management systems will enable oil multinationals and operators to pursue sustainable oil exploration and related operations. To prevent failure while being subjected to various loadings, these offshore platforms must be meticulously constructed, and then regularly maintained, monitored and inspected. Thus, this research contributes to the body of knowledge on asset management.

Based on the results on authorship, the top authors on asset management of offshore facilities presented authors with different values on their h-index, as the highest h-index was 5. The h-index was chosen as the metric indicator because it relates to the citation and significance of the research works conducted by a diverse range of authors across the globe. It was observed that the author with the highest number of publications was author Boutrot, J., with 5 publications on asset management of offshore facilities, though this author was not within the top five authors that have the highest h-index. The paper concludes that the management of these infrastructures requires frequent review with the application of sustainable asset management strategies. It also shows rising interest in monitoring and asset management in the oil and gas industry. However, the lack of access to high-quality data, transparency, adopting innovative technology, and providing effective decision support, are key issues in asset management. Thus, further work in the area can include the use of Artificial Intelligence (AI) and the Internet of Things (IoT) in asset management.

Author Contributions

Conceptualization, C.V.A.; software, C.V.A., S.B.B., A.R., D.B.M., I.A.J., A.S., A.K.O.; methodology, C.V.A., S.B.B.; investigation, S.B.B., A.R., D.B.M., I.A.J., A.S., A.K.O.; validation, C.V.A., S.B.B.; formal analysis, C.V.A., S.B.B., A.R., D.B.M., I.A.J., A.S., A.K.O.; resources, C.V.A., S.B.B., A.R., D.B.M., I.A.J., A.S., A.K.O.; writing—original draft preparation, C.V.A.; writing—reviewing draft, C.V.A., S.B.B., A.R., D.B.M., I.A.J., A.S., A.K.O.; funding acquisition, C.V.A., S.B.B., A.R., D.B.M., I.A.J., A.S., A.K.O.; project administration, C.V.A., S.B.B., A.R., D.B.M., I.A.J., A.S., A.K.O.; data curation, C.V.A., S.B.B.; visualization, C.V.A., S.B.B.; supervision, C.V.A., S.B.B.

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Data Availability

The supplementary data is also made available herewith. The link for the supplementary data used is https://data.mendeley.com/datasets/f4nf3wng4d.

The data citation is "Amaechi, C.V. (2022), "Supplementary Data for the Scientometric Analysis on Asset Management of Offshore Facilities", Mendeley Data, V1, doi: 10.17632/f4nf3wng4d.1".

Conflicts of Interest

All authors disclosed no conflict of interest.

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