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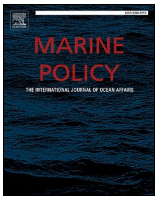

Biodegradable drifting fish aggregating devices: Current status and future prospects

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ABSTRACT

The structure, materials and designs of drifting Fish Aggregating Devices (dFADs) have generally remained rudimentary and relatively unchanged since they first came into use in the 1980 s. However, more recently, dFADs have been increasing in dimensions and the prevailing use of plastic components. Abandoned, lost or discarded dFADs can therefore contribute to the global marine litter problem. Transitioning to biodegradable and non-toxic materials that have a faster rate of decomposition, and are free of toxins and heavy metals, relative to synthetic materials, has been prescribed as an important part of the solution to reducing marine pollution from industrial tuna fisheries that rely on dFADs. This review of the current state of dFADs considers aspects related to the use of biodegradable materials in their construction, including; regulations related to dFAD materials, trials of biodegradable designs and materials and future alternatives. During the last decade, regulatory measures at tuna Regional Fishery Management Organizations (tRFMOs) have gradually moved towards the clear recommendation to use biodegradable materials in dFAD construction together with other measures limiting the number of active dFADs and the use of netting materials. However, to provide operational guidance, more clarity is needed, starting with a standardised definition of biodegradable dFADs among tRFMOs. Research involving dFAD natural and synthetic materials is required, along with improved data collection for monitoring the transition of dFAD materials against specified standards for biodegradable dFADs. In addition, alternative and complementary actions need to be explored to contribute to minimising adverse effects of dFADs on the environment. Acknowledging the current difficulties for the implementation of fully biodegradable dFADs in tuna fisheries, a stepwise process towards the implementation of commercially viable biodegradable dFADs should be considered.

1. Introduction

Tuna and other pelagic species tend to aggregate around floating objects in the open ocean. This associative behaviour of tuna has promoted the increasing use of drifting Fish Aggregating Devices (dFADs) in tropical tuna fisheries globally since the 1980 s. Since then, progress in dFAD-related technology, in particular electronic satellite tracked marker buoys fitted with echo-sounders, have allowed real-time monitoring of the geospatial position of dFADs and estimates of the associated tuna biomass. These technologies along with advances in other fishing equipment have progressively improved dFAD-fishing efficiency [1]. However, dFAD structure, materials and designs have remained

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rudimentary and virtually unchanged since the beginning of their use [2]. In the early days of tuna purse seine fishing, fishers looked out for natural floating objects like tree logs and branches [3]. Soon after, fishers started adding artificial elements to the logs to increase tuna attraction, such as attaching purse seine net to provide an underwater structure for fish to shelter, or cork line buoys to add flotation to the waterlogged objects. Eventually they moved to fully man-made dFAD constructions, characterized by increased dimensions and the use of nylon purse seine netting, other plastic components (e.g., bait buckets, synthetic sub-surface attractors, colourful plastic ribbons, tattered salt sacks), floating materials like bamboo and net corks, and pieces of metal wire or metal rings for ballast [2].

Designs and structures of dFADs vary among fleets and regions, but basically all consist of two parts: a floating or sub-surface (raft), and a hanging submerged (tail) structure (Fig. 1 and Table 1). The raft is generally built using several tightly bound bamboo canes as flotation, or wood and bamboo with a basic frame shape with additional flotation from net corks or floats. Recently, square or octagonal metallic frames are being used in some regions (e.g., Atlantic and Indian oceans) [4]. The raft is usually wrapped in black-coloured reused purse seine netting (often 5.1–8.3-inch mesh) and/or smaller mesh size netting (<2.7-inch mesh) to provide structural strength and reduce visibility to other vessels. Raffia or canvas are commonly used in addition to the netting, but rarely replace it completely, except in the Indian Ocean. The tail can also vary in shape and materials, but generally consists of open panels of small mesh size netting hanging underneath (mainly in the Atlantic and Pacific Oceans); or old purse seine netting tied in tight coils. Some fleets have recently replaced these net coils with polyester and/or cotton ropes, mainly in the Indian Ocean [5–7].

The long lifespan of petroleum-based plastic materials and the large amount of such material used in dFAD construction is contributing to increased negative impacts of dFADs on marine ecosystems [6,8–12]. Depending on the ocean and fleet, fishers consider that their dFADs have a functional lifespan of 6–12 months [2,10], with few dFADs functioning after one year. In fact, dFAD exchange or appropriation among vessels is occurring to different degrees in all regions and areas, resulting in skippers losing track of their dFADs well before their lifespan is reached (e.g., < 3 months in some regions). Between 50,000 to 100,000 dFADs are deployed globally each year [13,14]. Several studies have recently estimated that a significant proportion of deployed dFADs end up lost, abandoned or discarded [9,12,15], accounting for up to 40% of deployed dFAD in the case of the Atlantic Ocean [16]. These dFADs can in turn end up stranding in sensitive areas such as coral reefs [17–19,6, 20]. Once a dFAD track is accidentally lost or a dFAD is intentionally abandoned the owner requests the satellite buoy provider to deactivate the buoy, the dFAD and its buoy then become marine litter (MARPOL 73/78), and contribute to a global environmental problem that is present in all oceans and marine environments [21,22]. Adverse effects from dFADs were considered by Gilman et al. [23], and they classified tuna purse seine fishing using dFAD as one of the five most problematic fishing methods on a global scale.

Tuna Regional Fisheries Management Organizations (tRFMO), and the fishing industry, have adopted various measures to reduce the impact of dFAD structures on the marine ecosystem. These include reducing the number of daily active dFADs monitored by individual vessels (IOTC Res 19/02[1]; ICCAT Rec. 20–01[2]; IATTC C-21–04[3]; and WCPFC CMM-2021–01[4]); prohibiting dFAD activities in particular areas and/or months (IATTC C-21–04, ICCAT Rec. 20–01; and WCPFC CMM-2021–01); limiting the use of small mesh size netting material (< 2.7 in.) (ICCAT Rec. 20–01; IATTC C-19–01[5]; and WCPFC CMM-2018–01[6]) or prohibiting altogether the use of netting material in dFAD construction (IOTC Res 19/02; WCPFC CMM-2021–01); and promoting the use of natural or biodegradable materials (IOTC Res 19/02; ICCAT Rec. 19–02; IATTC C-19–01; and WCPFC CMM-2020–01). However, the problem of marine litter and stranding of dFADs remains unresolved. The use of alternative designs and materials such as natural biodegradable materials (e.g., bamboo canes, cotton, etc.), is being promoted as part of the solution. Biodegradable materials can degrade faster in the environment and are toxin and heavy metal free, thereby reducing long-term accumulation of lost or abandoned dFAD material in sensitive areas that can otherwise last for months to many decades [7]. Several stakeholders, including fishing companies, are now testing biodegradable materials, and some are already constructing part of their dFADs using these materials, most notably bamboo rafts and cotton ropes for the submerged structure [7]. However, except for some specific cases, dFADs are still mostly constructed out of highly durable synthetic materials including nylon nets, PVC and EVA flotation, and metallic rafts and weights [2, 24]. The only natural biodegradable materials regularly used are bamboo, in rafts, and in some cases, coconut or nipa palm leaves as attractors attached to the appendage [10]. The short lifespan observed for these biodegradable materials, which is shorter than that required by fishers on most occasions, is a key barrier to industry wide implementation of biodegradable dFADs [7]. Furthermore, the ready availability of cotton ropes and canvas in remote island locations is also problematic. Experimental biodegradable dFADs have been challenged by the structural stress suffered by traditional dFAD designs and most have shown considerably reduced lifespan [26]. Recently, new designs of biodegradable dFADs have been developed with the aim of decreasing the stress on the structure and thus increasing the durability and lifespan of the materials and the dFAD as a whole. The most notable example of such designs to date is the biodegradable JellyFAD [25].

This paper aims to provide guidance for advancement of biodegradable dFADs by: (i) reviewing the current status of the recommendations and resolutions of the different tRFMOs regarding the use of biodegradable materials in the construction of dFADs, (ii) proposing a definition of biodegradable dFADs and summarising the current status of alternative biobased plastic materials, (iii) summarising the experience of testing biodegradable dFADs at small and large scales, and (iv) proposing recommendations to advance the implementation of biodegradable dFADs.

2. Current policies on biodegradable dFADs

All tRFMOs have made progress towards addressing the impacts of derelict dFADs and have adopted recommendations and resolutions to gradually replace existing "conventional" dFADs with non-entangling and biodegradable dFADs. These efforts have included promoting research and encouraging the use of biodegradable materials in dFAD constructions to reduce synthetic marine litter (IOTC Res 19/02; ICCAT Rec. 20–01 and IATTC C-21–04; WCPFC CMM-2021–01). In this regard, the most ambitious resolution, Resolution 19/02, was adopted by the Indian Ocean Tuna Commission (IOTC) which states that; "*dFADs must be constructed with non-meshed materials from the 1st January 2020*", therefore, eliminating the use of netting altogether. In addition, Resolution 19/02 encourages the use of biodegradable materials in dFAD construction from the 1st January 2022: "*Contracting Parties and Cooperating (CPC) shall encourage their flag vessels to use biodegradable dFADs in accordance with the guidelines at Annex V with a view to transitioning to the use of biodegradable dFADs, with the exception of materials used for the instrumented buoys, by their flag vessel from 1 January 2022*". In the Atlantic Ocean, the International Commission for the Conservation of

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[1] IOTC Res 19/02

[2] ICCAT Rec 20–01

[3] IATTC C-21–04

[4] WCPFC CMM-2021–01

[5] IATTC C-19–01

[6] WCPFC CMM-2018–01

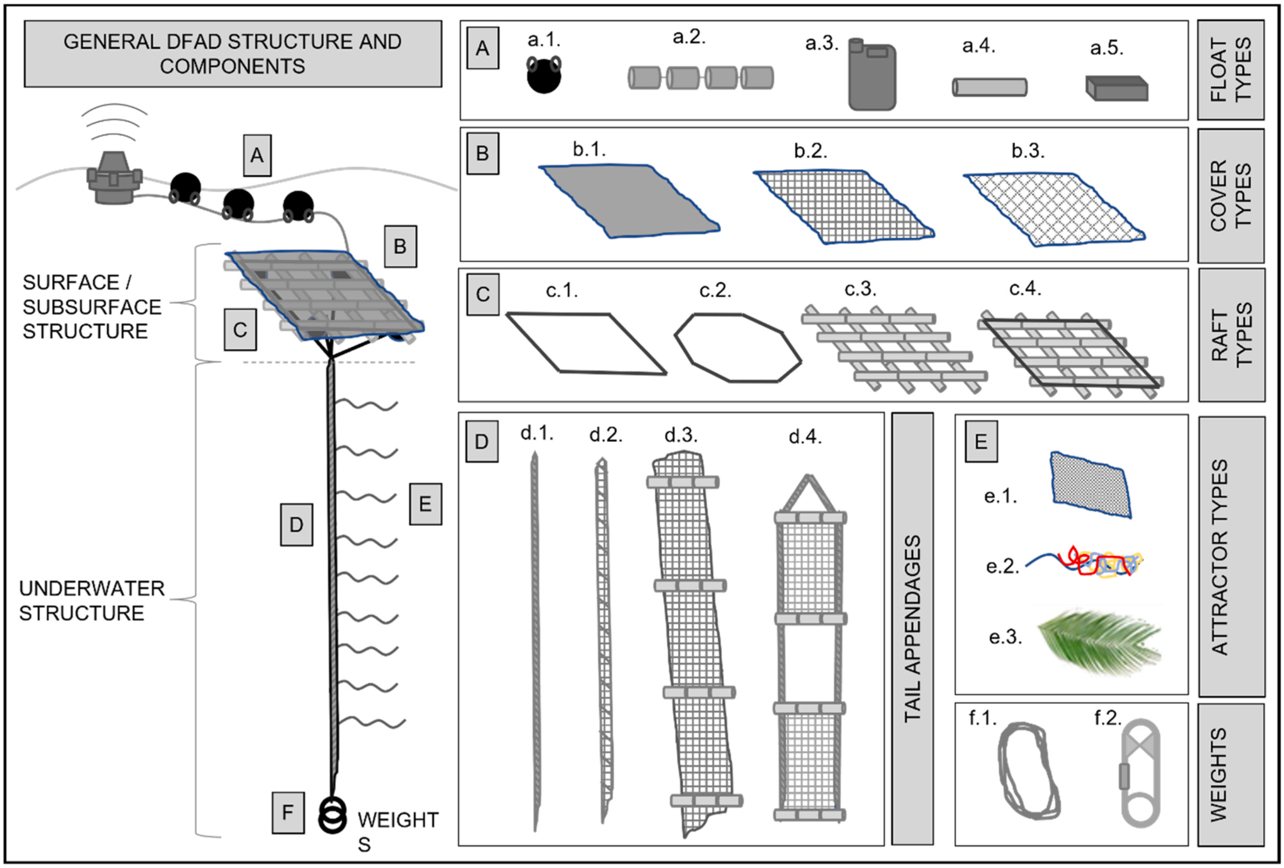

Fig. 1. General description of the structure (i.e., surface/subsurface and underwater structures) of the drifting Fish Aggregating Devices and its possible configurations and component parts.

Atlantic Tuna (ICCAT) has also adopted, in Recommendation 19–02, measures for the use of non-entangling dFADs and use of more sustainable materials. The change to non-entangling rafts and subsurface structures is aimed at reducing the entanglement of sharks, sea turtles or any other species. In the ICCAT recommendation the definition of non-entangling materials is less precise as it does not include any reference to the presence of meshed materials or mesh size, something which has been included in other tRFMO measures. In addition, to reduce the amount of synthetic marine litter, Recommendation 19–02 states that CPCs should "*endeavour that as of January 2021 all dFADs deployed are non-entangling, and constructed from biodegradable materials, including non-plastics, with the exception of materials used in the construction of dFAD tracking buoys*".

In the case of the Pacific Ocean, both the Inter-American Tropical Tuna Commission (IATTC) and the Western and Central Pacific Fisheries Commission (WCPFC) prohibit the use of entangling nets. If open mesh nets are used, the mesh size is restricted to $<$ 2.7 in. for the raft and tail. In the former case, it must be well wrapped around the whole raft so that there is no netting hanging below the dFAD when it is deployed, and in the latter case, if open mesh exceeds 2.7 in. it must always be tied tightly in bundles or "sausages" with weights attached to minimize the entanglement potential (IATTC C-19–01 and WCOPFC CMM-2018–01). The use of mesh nets will be completely prohibited in the Western and Central Pacific as of 1st January 2024 (WCPFC CMM-2021–01). In the IATTC area, all dFADs must meet the above mentioned criteria of low-entanglement risk and the use of biodegradable materials has been encouraged since 1st January 2019 (C-19–01), and in the WCPFC area, since 1st January 2020 (CMM-2018–01).

3. Bio-based plastics as alternative materials for dFAD construction

Due to the problems generated by petroleum-derived plastics, some plastic materials are evolving towards polymers derived from renewable biological resources (bio-based) and polymers that are considered biodegradable, and for which the degradation results from the action of naturally occurring micro-organisms [26]. In this sense, although bio-based plastic materials are not specifically described as an alternative to conventional plastics by the European Union (EU) Directive 2019/90, they may be a future option to consider for the construction of dFADs, depending on whether they become certified as biodegradable in the marine environment. However, the production of bio-based plastics is currently a small percentage, around 1%, of the global plastics production, and plastics certified as biodegradable in marine conditions are still limited and have limited functionality. Among those found with marine biodegradability certification (e.g., Novamont's Mater-Bi (complying with ISO 19679); NuplastiQ's BioBlend MB; NuPlastiQ CG (complying with ASTM D6691 and certified as "OK Marine" by TÜV Austria), most are based on biopolymers with very low functional properties (no more than 2–4 months durability). Furthermore, marine biodegradability standards are a guideline and there is a lack of information on clear requirements for conditions and time frames. Marine biodegradation standards are currently undergoing research and development, so that relevant bio-based plastic products can be introduced to the market.

It is important to note that just because a bio-based plastic is biodegradable in soil, it does not mean that it is biodegradable in a marine environment, as the physical and chemical conditions in each environment are different. Besides the certification and market limitations, the toxicity of chemical additives used in the production of bio-

Table 1
General description of the structure (i.e., surface/subsurface and underwater structures) of the drifting Fish Aggregating Devices and its possible configurations and component parts.

SURFACE / SUBSURFACE STRUCTURE	Type of floats	a.1 - Floats	Round shape high impact polystyrene float used to provide floatability (e.g., floatability of 5.8 kg/float) to the dFAD (use of 4–8 floats by FAD).
		a.2 - Corks	Net corks from ethylene vinyl acetate (EVA) usually recovered from old purse seine nets and used to provide floatability (e.g., mean floatability of ∼10.6 kg by cork) to the dFAD (use of 4–8 floats by dFAD).
		a.3 - Plastic containers	Plastic containers or bottles (e.g., volume of 5 L) of hexene copolymer used to provide floatability to the dFAD (e.g., use of ∼42 containers by dFAD).
		a.4 - PVC Pipes	Pipes (e.g., dimension of 1 m and ∼100–150 mm Ø) from polyvinyl chloride (PVC) used to provide floatability to the FAD (use of 2–4 pipes by dFAD).
		a.5 - Balsa tree	Wooden strips of different configuration made with a tree species (*Ochroma pyramidale*) found in south and central America and in several islands of WCPO. It is used to provide floatability to the dFAD.
	Type of cover	b.1 - Canvas	Non-meshed canvas, generally dark-coloured synthetic raffia (UV-resistant high-density polyethylene (HDPE)), used to cover the raft and to provide shade and prevent dFAD detection by others. The material for the construction of the canvas can be also from vegetal origin (e.g., cotton, natural raffia, abaca, etc).
		b.2 - Small mesh size net	Polyamide small mesh size (<7 cm or 2.5 in. stretched mesh) net, reused net from coastal purse seine fisheries or new. This net is used to strengthen the structure of the raft.
		b.3 - Large mesh size net	Polyamide large mesh size (>7 cm or 2.5 in. stretched mesh) net, from old Purse Seine tuna nets and used to strengthen the structure of the raft.
	Type of raft	c.1 - Metallic frame (square)	Square shape metallic frame raft (dimension ∼1.5–2 ×2 m) made with galvanized iron tubes. It is used as the main structure of the raft, providing strength and weight to try to submerge a bit the raft and prevent dFAD detection. Also, it is durable and easy to store onboard due to its small diameter (∼30 mm Ø).
		c.2 - Metallic frame (octagonal)	Octagonal shape metallic frame raft (dimension ∼1.8 ×2 m) made with galvanized iron tubes. It is used as the main structure of the raft providing strength and enough weight to try to slightly submerge the raft below the sea surface and prevent dFAD detection. Also, it is durable and easy to store onboard due to its small diameter (∼30 mm Ø).
		c.3 - Bamboo raft	Bamboo raft made with ∼10 bamboo canes (1.5–2 m and ∼70 mm Ø). It is used as the main structure of the raft providing strength and floatation to keep the raft near the sea surface.
		c.4 - Mixed raft (Bamboo and metallic frame)	Square shape raft built by putting together a metallic galvanized tube frame with bamboo canes across (details in previous types). It used as the main structure of the raft providing strength and a balance between the weight of the metal and the floatation of the canes.
UNDERWATER STRUCTURE	Type of tail appendage	d.1 - Rope	Tail made by polyethylene or natural origin (e.g., cotton) rope (∼20 mm Ø).
		d.2 - Tail tied in sausages	Tail with netting tied in coils or “sausages”, made by polyamide large (>7 cm or 2.5 in.) or small mesh (<7 cm or 2.5 in.) netting.
		d.3 - Open net tail	Tail with net in an open or stretched configuration, made with polyamide small mesh (<7 cm or 2.5 in.) netting. Often with bamboo canes across at several meter intervals to provide weight and keep the net panels open.
		d.4 - Tail with sails	Tail with netting tied in “sausages” or rope on the sides to which several polyamide small mesh (<7 cm) netting or raffia open panel sections or “sails” (e.g. 2–4 sections) are attached. This configuration is used mainly to control dFAD drift (e.g. slow down drift speed).
	Type of attractors	e.1 - Synthetic raffia or salt bags	Attractors done with synthetic raffia or reused

(*continued on next page*)

Table 1 (*continued*)

		salt bags tied to the tail to attract fish.
	e.2 - Frayed ropes	Synthetic (polyethylene) or natural origin (cotton, abaca, etc.) frayed coloured ropes, tied to the tail to attract fish.
	e.3 - Plant origin adornments	Plant origin attractors like palm leafs, tied to the tail to attract fish.
Weight	f.1 - Cable from PS	Weights made from surplus purse seine net cable.
	f.2 - Chain	Weights made by surplus chain from the purse-seine.

based plastic and their potential impacts on the marine environment are not clear enough yet [27]. For example, oxo-degradable plastics (i.e., conventional plastics mixed with an additive that quickly fragments into smaller and smaller parts but without breaking down at the molecular or polymer level) should not be considered as potential biodegradable materials for dFAD construction as, although they can breakdown quickly by oxidative chemical reagents, they continue to impact marine ecosystems by introducing microplastics into the food chain [28].

3.1. Biodegradable dFAD definition

The terms "natural" and "biodegradable" have often been used interchangeably to refer to these new alternative materials for dFADs by tRFMOs (IOTC Res. 19/02; ICCAT Rec. 19–02; IATTC C-19–01, and WCPFC CMM-20–01). However, the implementation of new materials for constructing biodegradable dFADs is not so straightforward, as a biodegradable material is subject to certain preconditions [29] and the definitions currently used by tRFMOs have been vaguely described and lack clear specification. Thus, despite the adopted resolutions and recommendations, more clarity is needed on how to actually classify a dFAD as being biodegradable. A standardised definition of biodegradable dFADs should be developed to provide guidance among tRFMOs, and such a definition should ideally be harmonized in the context of the Joint tRFMOs FAD Working Group. It is imperative that a definition identifies suitable materials, and realistic measures and materials standards for dFAD implementation and monitoring, and considers the state of availability, development and testing of suitable biodegradable materials.

Table 2 summaries the most relevant definitions proposed at tRFMOs during the last decade. These hinge on very similar important aspects. For example, Zudaire et al. [29], in line with Hampton et al. [30], considered aspects like type of materials and configuration, the environmental impacts, durability and functionality, and practical and economic viability. The ISSF definition also introduces impact aspects (i.e., dFAD beaching and marine litter) for which biodegradable dFAD should be a solution. In the interest of simplification, the IATTC Staff recommended to the Scientific Advisory Committee a narrower definition without referring to the harmfulness of the degradation outcome. A biodegradable dFAD definition should consider the international standards, regulatory frameworks and address minimum mandatory conditions for materials (e.g., permitted materials, derived-components and environmental considerations). In addition, it should be specified whether the term biodegradable can be applied to the final product or to the materials themselves (i.e., the dFAD, or the various component parts). In the latter case, each component may have different functionality/duration (lifespan), shape (thickness) and environmental impacts, as the dFAD has the potential to become a marine litter as whole or as disaggregated parts. Also, because abandoned, lost or discarded dFADs are hardly ever recovered by industry, recommended materials

Table 2
Summary of biodegradable dFAD definitions proposed at tRFMOs.

Source – Authors	Biodegradable dFAD definition
Hampton et al., 2017 presented at the 1st meeting of the Joint Tuna RFMOs FAD Working Group.	FADs constructed with natural or biodegradable materials that reduce the impact of beaching and debris. The term biodegradable is applied to a material or substance that is subject to a chemical process during which microorganisms that are available in the environment convert materials into natural substances such as water, carbon dioxide, and decompose organic matter. The time required for biodegradation of different materials varies. Some fishers believe that a FAD should last up to one year before degrading.
Zudaire et al., 2018 presented at 20th Working Party on Tropical Tuna (WPTT20) at IOTC.	A BIOFAD will be composed of non-netting form renewable lignocellulosic materials (i.e., plant dry matter) and/or bio-based biodegradable plastic compounds, prioritizing those materials that comply with international relevant standards or certification labels for plastic compostability in marine, soil or industrial compost environments. In addition, the substances resulting from the degradation of these materials should not be toxic for the marine and coastal ecosystems or include heavy metals in their composition. This definition does not apply to electronic buoys attached to FADs to track them.
ISSF Glossary.	Fish aggregating devices constructed with natural or biodegradable materials that reduce the impact of beaching and debris. The term biodegradable is applied to a material or substance that is subject to a chemical process during which microorganisms that are available in the environment convert materials into natural substances such as water, carbon dioxide, and decompose organic matter and that are non-toxic for the marine environment. The time required for biodegradation of different materials varies. Some fishers believe that a FAD should last up to one year before degrading.
IATTC Scientific Advisory Committee recommendation to the Commission (IATTC-100–03-ADD).	Non-synthetic materials and/or bio-based alternatives that are consistent with international standards for materials that are biodegradable in marine environments. The components resulting from the degradation of these materials should not be damaging to the marine and coastal ecosystems or include heavy metals or plastics in their composition."
IATTC Staff recommendation to the Scientific Advisory Committee.	A biodegradable FAD is composed of non-netting from organic materials and/or bio-based alternatives certified by international standards as biodegradable in marine environments.
WCPFC Scientific Commission 19 recommendation.	"Non-synthetic materials and/or bio-based alternatives that are consistent with international standards for materials that are biodegradable in marine environments. The components resulting from the degradation of these materials should not be damaging to the marine and coastal ecosystems or include heavy metals or plastics in their composition."

should be restricted to those that have been demonstrated to be biodegradable in the marine environment. Based on these aspects this review proposes the following definition:

> "*A biodegradable dFAD would be composed of non-netting form renewable lignocellulosic materials (*i.e.*, plant dry matter - here described as natural material) and/or bio-based compounds that comply with international relevant standards or certification labels for plastic biodegradability in marine environments. In addition, the substances resulting from the degradation of these materials should not be toxic for the marine and coastal ecosystems or include heavy metals in their composition. This definition does not apply to electronic buoys attached to dFADs to track them.*"

In parallel, tRFMOs should adopt mechanisms for data collection that would help to characterise the level of biodegradability of materials and their use in dFAD construction. This information would enable monitoring of the evolution and implementation of biodegradable dFADs under specific definitions and standards. Currently, tRFMOs collect data on dFADs through FAD logbooks and observer data, which can include information on the entanglement characteristics of materials, and the types of materials used in the construction of dFADs. More recently new data collection forms (e.g., ICCAT form CP51 and CP52) have been developed to collect data on marine litter, specifically lost or retrieved fishing gears. A future scenario of gradual implementation of biodegradable dFADs, classified into different categories of biodegradability, will require more comprehensive data collection by tRFMOs on materials and their amounts used in the dFADs (i.e., biodegradable versus non-biodegradable [31]). Otherwise, understanding of the use and implementation of biodegradable materials in dFAD construction will remain highly uncertain. Classifying the type of materials onboard is a challenge, due to some materials not being easily recognisable to an untrained eye, and conditions at sea are not always conducive to this type of monitoring of dFADs. Further training of observers on how to recognise and classify biodegradable components of dFADS would be useful.

4. Summary of small and large-scale experiences with biodegradable dFADs

In the last decade, public and privately funded projects have tested the suitability of several natural (lignocellulosic) materials to build biodegradable dFAD prototypes. Studies conducted on biodegradable dFADs date back to the early 2000 s [32–34]. However, most of these initial at sea tests with biodegradable dFADs were very limited in scale, yielding inconclusive results. These first trials with non-entangling biodegradable dFADs were mainly concerned with testing suitability of natural materials such as jute (*Corchorus capsularis*), sisal (*Agave sisalana*), and palm leaves (Family *Arecaceae*) [33]. Subsequently, small pilot projects with a few deployments of experimental biodegradable dFADs were conducted in the Indian and Atlantic oceans, also using bamboo rafts, sisal and jute ropes [35,36]. Similarly, the IATTC conducted a set of biodegradable anchored FAD tests in a controlled lagoon environment in Achotines (Panama). These anchored FADs were built with a floating structure made of bamboo canes and coconut (*Cocos nucifera*) shells and a tail either made with agave ropes and bamboo frames, high-resistance cotton (Genus Gossypium) canvas or a combination of both [37]. Other biodegradable dFAD trials, experimenting with ropes and canvas made from coconut fiber and high-grade cotton, were deployed by the private sector, with various purse seine companies (e.g., EU, United States of America, South Korea) testing them at sea during commercial fishing operations. In addition, EU purse seine companies sponsored a study to evaluate and compare biodegradable twine materials and their structural configuration (e.g., twisted, braided and bulked) for use in dFAD appendages [38]. Several plant-origin fibers such as cotton, sisal, hemp (*Cannabis sativa*) and linen (*Linum usitatissimum*) have been assessed under controlled conditions for suitability in the construction of ropes, considering biodegradation, resistance, reproducibility [38]. This study also considered availability in the market [38]. Similarly, the ISSF, in collaboration with the Marine Research Centre in the Maldives under the FAO Common Oceans Tuna project, tested various ropes made of organic materials (e.g., cotton, sisal and linen) under controlled conditions in the Maldives. The research showed that 100% cotton rope (20 mm diameter, 4 strands in torsion Z) best fulfilled the criteria to support the weight of the dFAD structure and attach the surface component of the dFAD with the deeper components [39]. ISSF in collaboration with an EU company also deployed 85 biodegradable dFADs with cotton rope tails in the Indian Ocean [39]. Other natural biodegradable materials that have been tested in small-scale experiments to make ropes and canvas include; agave and abaca (*Musa textilis*), coated, or not, with natural origin components [40]. Other options for materials, which have not yet been tested and may be potential candidates, include bamboo-derived textile fabric for the tail and other bamboo components for the raft/flotation. Balsa wood (*Ochroma pyramidale*) is available in some Latin-American countries and has shown promising results for dFAD flotation in the eastern Pacific Ocean experiment [37]. However, this material is not available in other parts of the world, so availability might limit it viability as a material for some fleets.

These initial small-scale trials provided a foundation to develop the larger-scale experiments launched in recent years in the Indian Ocean [7], and the eastern [37,40] and western [25] Pacific Oceans. The Indian Ocean project 'BIOFAD' funded by the EU and the ABNJ Common Ocean project, coordinated by AZTI (in consortium with Institut de Recherche pour le Développement, Instituto Español de Oceanografía, Seychelles Fishing Authority and ISSF) with the collaboration of the EU and South Korean purse seine fleets, has deployed 770 biodegradable dFADs built using natural materials like resistant cotton ropes/canvas and bamboo canes [7]. Although there were limited catches among the dFADs studied, no significant differences in catch rates were observed between biodegradable and conventional dFADs. Some materials such as cotton rope met the fishery expectations in terms of lifespan and are now a real alternative to plastic rope in the Indian Ocean [7]. Similarly, the eastern Pacific Ocean (EPO) project for biodegradable dFADs (called NEDs), that was funded by the EU, coordinated by IATTC, and framed within the Fishery Improvement Projects of EU (OPAGAC) and Ecuadorian (TUNACONS) shipowners' associations, deployed 780 biodegradable dFADs. The NEDs in this experiment are built using hemp, cotton, balsa wood and bamboo canes [37]. In the EPO, where 3 prototypes are being tested, the reported condition of the materials used in one prototype appear to be between 'excellent' to 'good' after at least two months of soak time. Preliminary results for the EPO experiment also showed similar catch rates per set between biodegradable and traditional paired dFADs [37]. These trials have led to initiatives from the industry itself. For example the fleet associated with TUNACONS is trialing a biodegradable dFAD prototype (Eco-FAD) tested in the IATTC program, and deployed 1401 "Eco-FADs" during 2021. This represents 20% of the total number of dFADs deployed by this fleet in that year, with abaca and balsa wood being the main tested materials [41].

With the experience gained from prior trials in which cotton material showed the most promising results, ISSF has recently developed the JellyFAD [25]. This is a new and innovative design of dFAD, based on drifters used by physical oceanographers. Results of previous experience testing biodegradable dFADs showed that in general the lifespan of biodegradable dFADs that maintain traditional designs, is shorter than that required by fishers (e.g., <6 months). The short lifespan of those biodegradable dFAD designs is thought to be, in part due, to the structural stress suffered by the traditional dFAD designs. Thus, in order to use organic materials, instead of plastics, and achieve an adequate dFAD lifespan, a paradigm shift in design may be required. Biodegradable dFAD structures could be re-designed to reduce structural stress by oceanic currents and wave action. The innovation of the biodegradable JellyFAD is that it drifts with quasi-neutral buoyancy, with the raft actually being sub-surface, and this reduces the structural stress and the need for flotation (i.e., plastic buoys). The JellyFAD is made with bamboo canes, and cotton ropes and canvas [25]. Recently, 70 JellyFADs have been deployed in the western Pacific Ocean in an ISSF project with the collaboration of a fishing company from the Federated States of Micronesia [25]. During 2022, new projects have been launched by OPAGAC to deploy around 350 JellyFADs in the Atlantic Ocean, as well as in the eastern Pacific Ocean. A new project by the WCPFC, funded by the EU, USA and ISSF, has begun further trials of JellyFADs in the Western and Central Pacific Ocean [42].

5. Future challenges

It is widely believed that the use of biodegradable materials in the construction of dFADs is an important part of the solution to minimise the adverse effects of abandoned, lost or discarded dFADs on the marine environment [7,23]. Searching for suitable biodegradable materials and testing them under real conditions is an essential step for their acceptance and application by tropical tuna purse seine tuna fisheries. However, obtaining clear results from continuous and large-scale testing, as well as finding materials with sufficient durability and longevity for industry use, is a challenges for the development of biodegradable dFADs. Recent large-scale trials in the Indian, Atlantic and Pacific oceans [7,25,37,40] have increased the sample size of monitored experimental biodegradable dFADs, which has allowed more robust analysis of their functionality both in terms of structure and design and their suitability for fishing over longer periods. Increasing the sample size for analysis is a key issue, given the high rates of dFAD appropriation and loss at sea. Results from experiments under real ocean conditions have shown high degradation of the tested biodegradable materials [7], with longevities being less than desirable for the fishery [2]. In addition to the search for and testing of materials, it is clearly necessary to explore new designs and rethink design concepts to increase the lifespan of the biodegradable dFADs [25]. The newly developed JellyFAD seems to be the most promising experimental dFAD design to date.

Despite the use of biodegradable materials in dFAD construction and the regulatory measures and recommendations by tRFMOs, alternative and complementary actions need to be explored to further reduce the adverse effects of dFADs on the environment. For now, dFAD recovery initiatives have been limited in time and space due to high cost and logistical difficulties/challenges associated with working in remote oceanic areas and limited resources [11,43]. However, dFAD retrieval programs involving multi-stakeholder regional cooperation and the commitment of purse seiner vessel operators have shown potential. An example is the FAD-Watch pilot project implemented in the Indian Ocean across 5 atolls in Seychelles, which provides a potential solution to partially reduce dFAD stranding and beaching events [19]. A similar program is currently under development in Palmyra atoll in the Western and Central Pacific Ocean [44]. A recent study in the Indian and Atlantic oceans has proposed coastal dFAD recovery programs as they estimated 20% of the abandoned, lost or discarded dFADs passed within 50 km of the major ports [16]. The feasibility of such retrieval programs could consider environmental information, such as ocean modelling and dFAD buoy trajectories, plus waste management options, including ways to transport and allow proper disposal and/or recycling of dFAD components, including buoys, in accordance with MARPOL Annex V (MARPOL 73/78). The management of recovered waste is another challenge for integrated waste management plans both on board vessels and in the major ports, where waste management standards and facilities can be highly variable, and depends on the location, the nature of the ports and who is responsible [45].

Other actions focused on avoiding dFAD stranding events could be more cost-effective. For example, evaluating the trade-off between the stranding rate associated with each deployment area and dFAD use [12,15], could help in decision making on alternative measures of spatio-temporal dFAD activity closures or the adaptation of measures already in place (e.g., dFAD closure in the Atlantic by Rec. 19–02). In addition, development of multi-stakeholder programs (with the commitment of purse seine vessel operators and their fishing companies) for dFADs reuse or exchange, by sharing tracking positions before deactivating dFAD buoys could help in reducing the number of abandoned, lost or discarded dFADs. Science-industry collaboration, like the ISSF Skippers Workshop program [46], the regular skippers' workshops organized by the IATTC and collaborators, or the tuna industry's programs such as the Codes of Good Practice [47] and "CAT DCP éco", "Requins" and "CAT Sélectivité " [48], are essential for making progress in the implementation of biodegradable materials and the management measures and operational fishing practices necessary to minimise dFAD impacts on the marine environment.

6. Recommendations

Based on the knowledge gained from research over the last decade on the development and use of biodegradable materials in dFADs construction, the following recommendations have been identified:

Definition and monitoring:

1. A harmonised definition, across tRFMOs, is urgently needed to establish clear guidelines, standards and a timeline for biodegradable dFAD construction and implementation.
2. Define updated data collection programs to better track industry use of biodegradable materials in dFADs.

Timeline for implementation:

1. Acknowledging the current difficulties for the implementation of fully biodegradable dFADs given that biodegradable materials for all dFAD components are not yet widely available (e.g., floating parts); a stepwise process, including a timeline, towards the implementation of fully biodegradable dFADs should be considered based on the current state of the art of materials and their regional availability, similar to ISSF's classification for dFAD entanglement risk [49].
2. Considering the degradable nature of the components used in biodegradable dFAD construction, i.e., materials more vulnerable to the environmental conditions and crew manipulation than synthetic ones [37], it might be necessary to adopt certain modifications in the fishing operations considering the shorter lifespan of biodegradable dFADs to prevent compromising their integrity (e.g., avoid rough handling manoeuvres, lifting them out of the water during the set, etc.).
3. Based on the recommendation made in the Indian Ocean BIOFAD project [7] different options/categories could be discussed in this stepwise and gradual transition process:

- Category I. This category corresponds to 100% biodegradable dFADs. This means all parts (i.e., raft and tail) of a dFAD are built with biodegradable materials. Used materials should fulfil the biodegradable dFAD definition.
- Category II. This category corresponds to dFADs using biodegradable materials for the whole dFAD except for the floating component (i.e., plastic floats). This means that all parts (i.e., raft and tail) of a dFAD are built with biodegradable materials fulfilling the definition for biodegradable dFAD but have additional non-biodegradable floatation elements.
- Category III. This category corresponds to dFADs using only biodegradable materials in the construction of the tail but non-biodegradable materials in the raft (e.g., synthetic raffia, metallic frame, plastic floats). This means all underwater hanging parts (i.e., tail) of a dFAD are built with biodegradable materials fulfilling proposed biodegradable dFAD definition.
- Category IV. This category corresponds to dFADs with all parts (i.e., raft and tail) only built partly or with non-biodegradable materials.

Progressively, as new biodegradable materials become available in the market, the percentage of biodegradability should increase for the construction of other parts of the dFADs (e.g., floats, buoy) in order to reach 100% biodegradability of dFADs as per the definition above. In the meantime, plastic based materials should be reduced as much as possible. Gradual modification of current dFAD designs, in terms of reductions in the amount of material (e.g., depth of tails) and the synthetic fraction used in their construction, should be promoted now, using results and lessons learned from all the global initiatives while medium- to long-term implementation of biodegradable dFADs is in progress.

Future research:

1. Replacement of non-biodegradable dFADs by partly/fully biodegradable dFADs still requires significant research and development to solve important practical, materials and technical design aspects necessary for biodegradable dFADs to be suitable for large-scale industry uptake.
2. Continued research is required to identify natural and synthetic materials that meet biodegradable dFAD definitions.

CRediT authorship contribution statement

IZ, MG, JM, GM, HM and JS conceived and planned the experiments. IZ, MG, HM, MTT, MR, MH, JL, LE, OCB, MC, MLR, JCB, PJP, SD contributed to data collection and summary. IZ, MG, HM, MTT, MR, MH, JL, LE, OCB, MC, MLR, JCB, PJP, SD contributed to the interpretation of the results. IZ took the lead in writing the manuscript. IZ, PH, JM, HM, LE, JL, conducted critical revision of the article. All authors provided critical feedback and helped shape the research, analysis and manuscript.

Data Availability

The authors do not have permission to share data.

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