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Artificial Bait for Tuna: A Comprehensive Review of Materials, Costs, and Effectiveness

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ABSTRACT: The declining availability of natural bait, such as small fish and squid, due to overfishing and ecosystem changes has driven the development of artificial bait as a sustainable alternative in tuna fisheries. This review examines advancements in artificial bait design, focusing on key aspects such as effectiveness, durability, and environmental sustainability. Materials like composite resin and aluminum have emerged as promising options due to their ability to replicate natural prey movements, enhance durability, and resist marine conditions. While plastic-based bait offers cost advantages, its environmental impact and lower durability remain concerns. The integration of biodegradable materials and fluorescent coatings further enhances bait visibility and minimizes ecological footprints. By innovating bait size, shape, and material selection, artificial bait can effectively reduce reliance on natural stocks while promoting sustainable fishing practices. However, further research is needed to refine hydrodynamic properties and assess long-term ecosystem impacts in diverse fisheries contexts.

KEYWORDS: Artificial bait; Tuna fisheries; Sustainable fishing practice; Composite resin; Environmental impact

I. INTRODUCTION

Tuna fisheries have long relied on natural bait, such as small fish and squid, due to their effectiveness in mimicking natural prey and attracting target species. However, the sustainability of this practice is increasingly under threat. Overfishing and environmental changes have significantly depleted natural bait stocks, leading to rising costs and reduced availability. This scarcity not only jeopardizes the economic stability of tuna fisheries but also has broader ecological consequences, as the overexploitation of bait species disrupts marine ecosystems and food chains [1], [2].

The urgency to adopt sustainable practices has prompted interest in artificial bait as a viable alternative. Artificial bait offers several advantages over natural bait, including durability, customizability, and reduced ecological impact. Composite resin and aluminum have emerged as promising materials for artificial bait due to their unique properties. Composite resin provides flexibility in design, enabling the creation of shapes and movements that replicate live prey, while aluminum ensures structural stability and resistance to seawater corrosion [3], [4]. These materials not only enhance the effectiveness of artificial bait but also offer long-term cost efficiency, reducing the frequency of replacement.

Innovative approaches, such as the use of Fish Aggregating Devices (FADs), have also been explored to improve catch rates without exacerbating overfishing. When combined with responsible fishing techniques, FADs can mitigate some ecological pressures associated with natural bait scarcity [5]. Additionally, advancements in artificial bait design, including the integration of fluorescent coatings and scent-mimicking compounds, have shown potential to rival or even surpass the effectiveness of natural bait in attracting target species [6], [7].

Despite these advancements, challenges remain. Fish responses to bait can vary significantly based on species, habitat, and environmental conditions. While artificial bait offers a durable and environmentally friendly alternative, its effectiveness still depends on its ability to replicate the sensory and visual characteristics of natural bait. Addressing these challenges requires a holistic approach that considers hydrodynamic properties,

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design innovation, and the ecological implications of artificial bait usage.

This study reviews the current state of artificial bait development, with a focus on material properties, design effectiveness, and sustainability. By addressing these aspects, the study aims to support the transition toward more sustainable fishing practices that reduce dependency on natural bait and mitigate environmental impacts.

II. METHOD

This review adopts a systematic approach to analyze and synthesize existing literature on artificial bait development for tuna fisheries. A comprehensive search was conducted across multiple scientific databases, including PubMed, Scopus, Web of Science, and Google Scholar, using keywords such as "artificial bait,""tuna fisheries,""sustainability in fishing,""composite resin bait," and "biodegradable materials in fisheries." The search primarily targeted articles published between 2000 and 2024 to ensure the inclusion of the most recent advancements, while significant older works were also incorporated to provide historical context.

The selection of studies followed specific inclusion and exclusion criteria. Peer-reviewed articles, reviews, and reports focusing on artificial bait materials, design, and sustainability, as well as comparative studies of natural and artificial bait, were included. Studies unrelated to tuna fisheries, lacking data on bait characteristics, or published in non-English languages were excluded. Relevant data were extracted from the selected studies, emphasizing material properties such as durability, hydrodynamics, and environmental impact, alongside bait effectiveness, production costs, and ecological consequences. Particular attention was given to the ability of artificial bait to mimic natural prey in terms of movement, visibility, and aroma, as well as its economic feasibility and ecological benefits in reducing the reliance on natural bait stocks.

The extracted information was systematically organized into themes, including material innovation, economic viability, and environmental sustainability. A comparative analysis was conducted to evaluate the strengths and limitations of artificial bait relative to natural bait, highlighting trends, gaps, and opportunities within the field. To ensure the reliability of findings, the quality of the included studies was assessed based on criteria such as study design, sample size, and relevance to the objectives of the review.

By integrating insights from these studies, this review aims to provide a comprehensive understanding of the current advancements in artificial bait for tuna fisheries. The synthesis focuses on identifying sustainable practices, economic efficiencies, and potential areas for future research to support the transition to more environmentally responsible fishing practices.

III. RESULTS AND DISCUSSION

Natural Bait

Natural bait, such as small fish and squid, has long been the primary choice in tuna fisheries due to its ability to mimic natural food sources and attract target fish. The characteristics of natural bait, which resemble real prey, make it highly effective in catching tuna, particularly through movements and aromas that stimulate the predatory response of fish [8]. Tuna, with their keen sense of smell and vision, tend to be more attracted to live bait exhibiting signs of movement and natural scent compared to artificial bait [3]. However, the use of natural bait also faces several limitations, such as availability constraints caused by declining populations of bait species due to overfishing and environmental changes [1], [9]. This decline not only reduces operational efficiency but also increases costs for fishers, given the rising prices of natural bait as stock becomes scarcer [2].

Figure 1. An example of fish natural bait

Despite these challenges, natural bait has a key advantage in its effectiveness in attracting target fish better than most artificial alternatives. Some studies indicate that using squid as bait in tuna fisheries can enhance catch rates, thereby reducing reliance on small fish stocks that are already limited [8]. On the other hand, the environmental challenges posed by the use of natural bait, including its impact on marine ecosystems and food chains, highlight the need for more sustainable solutions. The decline in natural bait species populations affects the overall marine ecosystem and creates ecological pressure that can disrupt habitat balance [9].

The broader ecological consequences of natural bait use are significant. The removal of bait species can disrupt local ecosystems and introduce risks associated with invasive species [10]. Furthermore, the addition of bait into marine environments can alter trophic dynamics and increase competition among species [11]. Such disruptions suggest that while natural bait may

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initially enhance fishing outcomes, its long-term ecological costs necessitate a reevaluation of its use in fisheries management.Meanwhile, the advancement of artificial baits offers a promising alternative. Research indicates that artificial baits can replicate the sensory cues that attract fish, potentially achieving comparable or even improved catch rates without the ecological drawbacks of natural bait harvesting [6].Therefore, developing more durable and sustainable artificial bait is becoming increasingly important in efforts to reduce reliance on natural bait and support the sustainability of the tuna fishing sector.

Artificial Bait

Artificial bait has been developed as a promising alternative to address the limitations of natural bait in tuna fisheries. Several studies indicate that the use of composite materials, such as resin and aluminum, can produce bait that is not only durable but also effective in attracting the attention of target fish [3]. Composite resin allows for the creation of shapes and movements resembling live prey, enhancing the visual appeal of the bait. On the other hand, aluminum provides structural strength and resistance to seawater corrosion, making it more durable in harsh marine conditions and potentially reducing the costs associated with frequent bait replacement [4].

In addition to durability, artificial bait is also designed with considerations for effectiveness in improving catch rates. Research shows that artificial bait equipped with physical attributes such as fluorescent colors or textures resembling prey can increase visibility and stimulate the feeding response of target fish [3], [6]. The effectiveness of artificial bait in attracting fish can also be enhanced through aroma modifications or coatings that mimic the natural scent of prey, which is a critical factor in attracting predatory fish like tuna [7].

However, the application of artificial bait also faces some challenges, particularly related to performance consistency across various marine environments. Some studies suggest that while artificial bait can rival natural bait under certain conditions, its effectiveness may decline in different environments, as fish exhibit varying responses to bait depending on habitat conditions and previous fishing experiences [12], [13]. Additionally, in some cases, fish show a preference for natural bait, especially if artificial bait fails to adequately mimic the sensory characteristics of natural bait, such as realistic scent and texture [14].

Figure 2. An example of artificial lures designed to mimic small fish.

Thus, while artificial bait offers a more durable and environmentally friendly solution compared to natural bait, its development requires a holistic approach that considers hydrodynamic aspects, color, and aroma tailored to the target species and specific aquatic conditions. This approach will help maximize the effectiveness of artificial bait in supporting the sustainability of the tuna fishing sector while reducing pressure on diminishing natural bait stocks. Table 1 compares the characteristics of natural and artificial bait in tuna fisheries, focusing on parameters such as effectiveness, durability, cost, environmental impact, and adaptability to environmental conditions. The table highlights the strengths of artificial bait in durability

Table 1. Comparative Analysis of Natural and Artificial Bait Characteristics in Tuna Fisheries

Parameter	Natural Bait	Artificial Bait	Reference
Effectiveness in Attracting Fish	High, due to movements and aromas resembling natural prey, effectively attracting target fish like tuna.	Quite effective, especially if equipped with physical attributes and aromas similar to prey, such as texture and fluorescent colors.	[8], [3], [6]
Durability	Prone to damage and spoilage, requiring frequent replacement.	Very durable; materials like composite resin and aluminum provide high resistance in marine environments.	[4], [3]
Cost	Tends to be high due to scarcity caused by overfishing, especially	More economical in the long term as it does not require as frequent replacement as	[1], [2]

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Parameter	Natural Bait	Artificial Bait	Reference
	for species like small fish and squid.	natural bait.	
Environmental Impact	Potentially harmful to marine ecosystems due to overfishing of specific species used as bait.	More environmentally friendly, reducing dependence on natural species and easing pressure on ecosystems.	[9], [8]
Impact of Environmental Conditions	Highly dependent on water conditions and seasons; availability of certain species may vary.	Consistent in various environmental conditions; can be designed to meet specific needs based on target species.	[12], [13]
Aroma and Sensory Features	Has a natural aroma that strongly attracts fish; this aroma is difficult to replicate perfectly in artificial bait.	Aroma can be added, but it is often less effective compared to the natural scent of live bait.	[7], [14]
Impact on Bycatch	Effective in reducing bycatch when used specifically for target species.	Depends on design; can be developed to minimize bycatch, although in some cases it is less selective.	[16], [8]

Effectiveness of Bait

The effectiveness of bait in tuna fisheries is significantly influenced by its ability to attract the attention of target fish through visual, sensory, and aromatic characteristics that mimic natural prey. Natural bait, such as small fish and squid, is generally considered more effective because it possesses movements and odors that align with the natural feeding preferences of tuna, enhancing attractiveness and catch potential [8], [9]. Additionally, studies have shown that fish tend to respond more quickly to natural bait than artificial bait due to stronger olfactory and visual stimuli, which are challenging to replicate artificially [3].

However, despite the high effectiveness of natural bait, its limited availability and increasing costs pose significant challenges, driving the development of more durable and economical artificial bait [1], [2]. Artificial bait made from composite materials, such as resin and aluminum, offers a reliable alternative due to its high durability in harsh marine conditions and the ability to be customized for specific scenarios, such as the use of fluorescent colors to improve underwater visibility [4], [6]. Artificial bait also allows for variations in design and size, which can be optimized to attract fish in specific situations or for specific species.

Nevertheless, the effectiveness of artificial bait still depends on its adaptation to the target species and specific environmental conditions. Some studies indicate that fish, particularly tuna, may show a preference for natural bait, especially if artificial bait fails to adequately replicate the natural scent and movements produced by live bait [14]. In this context, although artificial bait offers a more economical and environmentally friendly solution, its success in improving catch rates will depend on developments that account for fish responses to various physical, visual, and sensory characteristics of bait [3], [7].

Movement and Hydrodynamics of Bait

The movement and hydrodynamics of bait are critical aspects that influence the effectiveness of bait in attracting target fish, particularly in tuna fisheries. Movement that mimics natural prey can enhance the bait's attractiveness to predatory fish, which naturally respond to changes in motion within the water [3]. Natural bait, such as small fish or squid, tends to exhibit spontaneous movements resulting from natural interactions with water currents, creating realistic motion patterns that are appealing to tuna. However, replicating these natural movements in artificial bait poses a unique challenge, particularly due to design limitations in producing similar hydrodynamic motions [8].

The use of composite materials such as resin and aluminum in artificial bait enables the simulation of natural movements more effectively through modifications in hydrodynamic design. Composite resin, for example, provides flexibility to create shapes and sizes of bait that interact optimally

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with water currents, generating motions such as flapping or undulating that mimic live prey [3], [4]. Additionally, aluminum as a structural component offers stability and durability for artificial bait, enabling designs that withstand seawater flow without compromising flexibility in movement.

Research also shows that the physical characteristics of bait, such as size, texture, and buoyancy, play an important role in influencing hydrodynamics. Bait designed with appropriate texture and weight distribution can adapt to various water currents, resulting in movements that are attractive to target fish [6]. The movements generated by artificial bait designed with hydrodynamic principles not only increase the likelihood of attracting fish but also reduce the risk of bycatch, as their motion can be tailored for specific species sensitive to particular movement patterns [12].

Thus, a design approach that considers bait hydrodynamics enables the development of artificial bait that is more effective and efficient in diverse environmental conditions. Optimizing bait movement through careful hydrodynamic design provides a more sustainable and economical alternative to natural bait while supporting ecologically responsible fishing practices [7].

Bait Materials

Composite resin allows bait to adapt to water currents, imitating movements that are attractive to target fish such as tuna while also providing greater resistance to harsh marine environments [3]. Besides resin, aluminum is another preferred material due to its structural strength and corrosion resistance, making artificial bait more durable than natural bait or other alternative materials [4]. The combination of composite resin and aluminum produces bait with both flexible movement and high durability.In addition to durability, bait materials are also designed to enhance visual and sensory appeal. Some studies show that the application of fluorescent coatings on bait surfaces can increase visibility underwater, particularly in waters with high turbidity. Materials with bright colors or light-reflecting properties can attract target fish more effectively and improve catch rates [6]. Some studies even develop bait materials that can release prey-like aromas by using coatings or composites containing organic or synthetic extracts to attract fish more effectively [7].

Although materials such as composite resin and aluminum offer many advantages, the effectiveness of artificial bait still depends on the material's ability to meet specific fishery requirements. For instance, bait that is too rigid or heavy may not be suitable for all water types or fish species. Therefore, innovations in artificial bait materials must strike a balance between durability and flexibility, as well as the ability to create sensory appeal that closely resembles natural bait [14]. With the right approach, artificial bait materials can become a more economical and sustainable solution, reducing dependence on natural bait and supporting environmentally friendly fishing practices.

Table 2 details the material properties of various artificial bait types, including composite resin, aluminum, wood, and plastic. It evaluates their durability, ability to mimic natural movements and aromas, visual appeal, environmental impact, and production costs, providing a comprehensive overview of material suitability for fisheries.

Table 2. Material Properties of Artificial Bait and Their Suitability for Fisheries

Parameter	Metal Material	Composite Material	Wood Material	Plastic Material	Reference
Durability	Highly durable and resistant to corrosion, especially in saltwater environments.	Durable and can be designed to replicate the flexibility of natural movements.	Prone to water damage, requiring additional maintenance.	Quite durable but may degrade in harsh marine environments.	[4], [3]
Ability to Mimic Natural Movement	Less flexible, difficult to mimic natural movement despite having a strong structure.	Excellent, as it can mimic natural movement by adjusting weight and shape.	Movements are fairly natural but limited to certain shapes.	Can mimic movement but often appears more rigid.	[3], [8]
Ability to	Cannot mimic	Aroma can be	Can mimic natural	Synthetic aroma can	[7], [14]

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Parameter	Metal Material	Composite Material	Wood Material	Plastic Material	Reference
Mimic Aroma	natural aroma; generally not used to enhance scent appeal.	added through coatings or material mixtures.	aroma due to organic material but the scent fades quickly.	be added but is not long-lasting.	
Visual Appeal	Can be polished or painted with contrasting colors but limited in design flexibility.	Can be coated with fluorescent colors or contrasting designs.	Limited to the natural color and texture of wood.	Easily colored and available in a wide range of designs and colors.	[6], [3]
Environmental Impact	Not environmentally friendly if not properly managed, as it may contribute to metal waste.	More eco-friendly if biodegradable composites are used.	Environmentally friendly but production and maintenance may negatively impact ecosystems.	Not environmentally friendly as plastic degrades very slowly.	[10], [7]
Production Cost	Generally high, depending on the type of metal used.	Fairly expensive depending on the type of composite used, but can be an economical investment in the long term.	Relatively low but requires frequent replacement.	Low production costs but with significant environmental impacts.	[4], [3]

Color of Bait

The color of artificial bait plays a crucial role in attracting the attention of target fish, particularly in fisheries that utilize visual appeal as the primary attractant. Research shows that vibrant or fluorescent colors can enhance the visibility of bait underwater, especially in waters with high turbidity or in low-light conditions [6]. Bright colors, such as yellow, red, and orange, are often used for artificial bait due to their ability to attract the attention of predator fish that are sensitive to color contrasts, thereby increasing the effectiveness of the bait in stimulating feeding responses [3]. Additionally, fluorescent colors can reflect light and remain visible in deep water, which is the habitat of several large fish species, including tuna.

Other studies highlight that fish color preferences may vary based on species, habitat conditions, and time of day. For instance, during the day in bright shallow waters, fish may be more attracted to less conspicuous colors, while in nighttime or deep-water conditions, bright or fluorescent colors become more effective [12]. In certain conditions, the use of color combinations in artificial bait is also recommended to mimic natural prey patterns or provide a more realistic appearance, especially for bait used in tuna fishing and other predators that respond quickly to visual cues.

However, the effectiveness of color in artificial bait depends not only on the color itself but also on its interaction with the material used, as some materials can reflect light better than others. For example, composite resin and plastic can be coated with fluorescent or metallic colors to enhance their visual appeal [6]. Thus, selecting the appropriate color for artificial bait, tailored to environmental conditions and target species, becomes an effective strategy to sustainably improve catch rates while minimizing the ecological impact of using natural bait.

Table 3 analyzes the effectiveness and visibility of different bait colors in various fishing conditions. It evaluates parameters such as visibility in shallow and deep waters, attractiveness to predator fish, color durability under different light conditions, and habitat suitability, emphasizing the importance of selecting appropriate colors for specific environments.

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Table 3. Color Effectiveness and Visibility in Artificial Bait for Various Fishing Conditions

Parameter	Red Color	Yellow Color	Orange Color	Blue/Green Color	Fluorescent Color	Reference
Visibility in Shallow Waters	High, stands out in shallow waters, especially in bright conditions.	Very visible in shallow waters with adequate light.	Highly visible, especially in shallow to moderate depths.	Moderately visible in shallow waters but not as vibrant as brighter colors.	Very visible, ideal for various conditions, including low-light situations.	[6], [3]
Visibility in Deep Waters	Less effective as red tends to lose intensity at certain depths.	Less effective as intensity diminishes in deep waters.	Fairly good but color intensity may decrease.	Highly effective in deep waters, especially blue, which is more stable at depth.	Highly effective as it reflects light at depth and remains visible in low-light conditions.	[12], [7]
Effectiveness in Attracting Predator Fish	Effective for fish that respond to bright and contrasting colors; often attracts predators like tuna.	Highly effective for fish responsive to bright and contrasting colors.	Effective in attracting target fish responding to striking visual stimuli.	Fairly effective, especially for species preferring neutral or less conspicuous colors.	Highly effective in attracting attention due to its light-reflecting properties and strong visual stimuli.	[3], [6]
Color Durability in Various Light Conditions	Less durable in low-light or turbid water conditions.	Suboptimal in low-light or murky water conditions.	Fairly good across light conditions but can decrease in turbid waters.	Good in low-light conditions, particularly blue, which is more stable.	Excellent, can reflect light and remain effective in low-light and murky water.	[3], [12], [7]
Suitability for Various Habitats	Best suited for shallow waters with good lighting.	Suitable for shallow to moderate waters.	Suitable for shallow to moderate waters.	Suitable for deep waters and dimmer habitats.	Suitable for all habitats, including deep waters and high-turbidity conditions.	[6], [3]

Size and Shape

The size and shape of artificial bait play a critical role in attracting target fish, especially in tuna fisheries and other predatory species. The appropriate size of bait can enhance catch effectiveness, as fish tend to respond to bait resembling their natural prey in terms of dimensions and proportions [3]. Bait that is too large or too small is often less appealing to specific species, while optimal sizing can maximize feeding responses and improve catch success. For instance, research indicates that predator fish are more attracted to medium-sized bait resembling their natural prey in their habitat, although this can vary depending on the species and location [4].In addition to size, the shape of bait influences fish responses, as shapes resembling live prey are generally more effective in attracting attention. Bait designed with aerodynamic or streamlined shapes enables more natural movements in the water, creating visual appeal similar to small fish or other marine organisms [6]. Artificial bait shaped to mimic natural prey, such as small fish or squid, can stimulate predatory responses more effectively, as their movement patterns and silhouettes appear more realistic. Furthermore, some studies indicate

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that bait designed using lightweight composite materials can maintain an ideal shape without adding excessive weight, thereby providing stability and flexibility to artificial bait [6].

In certain cases, bait design is also adjusted to reduce bycatch or unintended species capture. Bait with more specific shapes can help target certain fish species, thereby reducing the number of non-target species accidentally caught [7]. Therefore, selecting the right size and shape of bait can enhance the effectiveness of artificial bait in fisheries while supporting more selective and sustainable fishing practices.

Table 4 examines the impact of bait size and shape on performance in tuna fisheries. It compares small, medium, and large baits, as well as streamlined shapes and those resembling natural prey. The table underscores the importance of optimizing size and shape to attract target species while maintaining ease of handling and adaptability to currents.

Table 4. Size and Shape Impact on Artificial Bait Performance in Tuna Fisheries

Parameter	Small Size	Medium Size	Large Size	Streamlined Shape	Shape Resembling Natural Prey	Reference
Attraction to Small Fish	Effective for small species but less appealing to large predators	Moderately attractive to small fish, yet still capable of catching predator attention	Less effective for small fish, more suitable for large predators	Attractive to both small fish and predators due to natural movement in water	Effective in resembling natural prey, appealing to both small fish and predators	[4],[3]
Attraction to Large Predators	Less appealing to large predators	Highly attractive to predators due to its resemblance to natural prey	Very appealing, especially for large predators in deep or open water	Stable and naturally moving, appealing to predators	Resembling prey like small fish or squid, highly appealing to predators	[3],[6]
Ease of Handling	Easy to use but not always stable in strong currents	Relatively easy, more stable than small size	Harder to handle due to weight, but stable in deep waters	Stable in currents due to aerodynamic shape	Stable in water, but complex shapes may be harder to attach	[6],[4]
Visibility in Water	Easily visible in clear water, but less visible in murky or deep water	Good for clear water and moderate light conditions, quite visible	Clearly visible in deep and murky waters, but may be excessive in shallow waters	Clearly visible in various conditions due to light-reflecting streamlined shape	Highly visible in varied conditions, especially with attractive colors	[3],[12]
Adaptability to Currents	Unstable in strong currents, suitable for calm waters	Stable in moderate current conditions	Stable in strong currents and deep waters	Highly adaptive to varied currents, maintaining stability and natural movement	Stable but complex shapes might reduce agility in strong currents	[12],[7],[3]

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Parameter	Small Size	Medium Size	Large Size	Streamlined Shape	Shape Resembling Natural Prey	Reference
Effectiveness in Reducing Bycatch	High, as it attracts small fish, reducing potential bycatch of predators	Effective in targeting certain predators but may be less selective in some cases	Less effective in reducing bycatch, may attract attention from other large predators	Effective as streamlined shapes can be adjusted to avoid non-target species	Moderately effective in targeting specific species, but may still catch non-target species	[7],[4]

In certain cases, bait design is also adjusted to reduce bycatch or unintended species capture. Bait with more specific shapes can help target certain fish species, thereby reducing the number of non-target species accidentally caught (Bacheler et al., 2018). Therefore, selecting the right size and shape of bait can enhance the effectiveness of artificial bait in fisheries while supporting more selective and sustainable fishing practices.

Cost and Production

The cost and production process of artificial bait are important factors to consider in the development of sustainable bait for fisheries. High-quality artificial bait typically requires an investment in durable materials, such as composite resin and aluminum, which, although initially more expensive, offer long-term benefits due to their durability and greater effectiveness compared to natural bait [4]. Composite resin, for example, provides flexibility in design, allowing bait to be created with more realistic shapes and textures. However, the production process for this material requires specialized techniques, such as molding and coating, which add to production costs [3]. Similarly, aluminum as a structural material offers excellent stability and resistance to corrosion but requires more complex manufacturing processes, such as cutting and welding, to ensure the bait design meets performance standards required in marine environments.

Furthermore, in efforts to create environmentally friendly artificial bait, production costs may increase with the use of more innovative materials, such as biodegradable components or natural dyes that mimic the appearance of prey. However, this approach reduces reliance on natural bait, potentially resulting in long-term savings and reduced ecological impacts [7]. Meanwhile, plastic-based bait tends to be cheaper and easier to produce on a large scale using injection molding techniques, but it has limitations in durability and poses negative environmental impacts due to its slow degradation [6].

Table 5 summarizes the cost and production characteristics of artificial bait materials, including composite resin, aluminum, wood, and plastic. It covers factors such as initial production cost, production complexity, durability in marine environments, long-term effectiveness, environmental impact, and material availability, providing insights into economic and sustainable bait production.

Table 5. Cost and Production Characteristics of Artificial Bait Materials

Parameter	Composite Resin Material	Aluminum Material	Wood Material	Plastic Material	Reference
Initial Production Cost	High, requires special materials and molding techniques	High, especially for cutting and welding processes to achieve desired shapes	Moderate, more affordable but requires additional maintenance to withstand marine conditions	Low, easily mass-produced at low cost	[4], [3]
Production Process	Complex; involves resin molding and	Complex; involves cutting, welding, and	Simple; usually involves basic cutting and coating,	Very simple; mass production via injection molding	[6], [7]

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Parameter	Composite Resin Material	Aluminum Material	Wood Material	Plastic Material	Reference
	coating processes for durability and flexibility	painting for corrosion resistance	but more prone to damage	allows for low-cost and quick production	
Durability in Marine Environment	Very good; withstands harsh marine conditions and corrosion	Extremely high; very durable and stable in saline water	Fairly good but requires coating or maintenance to prevent damage	Moderate; limited durability, especially under UV exposure and harsh marine conditions	[3], [12]
Long-term Effectiveness	High; durable and doesn't require frequent replacement, suitable for long-term investment	Very high; rarely needs replacement, reusable in extreme conditions	Moderate; natural material but easily damaged, requiring periodic replacement	Low; typically wears out quickly and may contribute to marine plastic waste	[7], [4]
Environmental Impact	Relatively eco-friendly if using biodegradable composite materials	Environmentally friendly if managed properly, but may cause metal pollution if not disposed of correctly	Fairly eco-friendly, but wood production processes can contribute to deforestation	Not environmentally friendly; plastic is non-biodegradable and causes significant marine pollution	[10], [7]
Material Availability	Available but more expensive, depending on the type of resin used	Limited and tends to be expensive; dependent on availability of corrosion-resistant metals	Easily available, but limited for certain wood types suitable for marine environments	Very easily available and inexpensive; plastic is the most commonly used material worldwide	[4], [3]

Overall, although artificial bait made from high-quality materials has higher initial costs, the manufacturing processes involving technologies such as resin molding and corrosion-resistant metals like aluminum offer long-term advantages. The development of more efficient production methods, such as automation in molding and coating, can help reduce costs while increasing the availability of artificial bait for the fisheries industry [12].

Artificial bait offers significant advantages in terms of reducing the ecological impact of fishing activities. The use of composite resin and aluminum materials, particularly when integrated with biodegradable elements, reduces dependency on natural bait, thereby alleviating fishing pressure on small fish and squid populations [5], [15]. This reduction in overharvesting helps maintain the balance of marine ecosystems and minimizes disruptions to food chains. Additionally, artificial bait does not contribute to the spread of invasive species, a risk associated with the transport and use of live bait in new environments [6].

However, the production of artificial bait, particularly those using non-biodegradable plastics, can contribute to long-term marine pollution if discarded improperly. Plastics degrade very slowly in marine environments, posing threats to aquatic ecosystems and wildlife [9]. The transition to biodegradable materials in artificial bait manufacturing is essential to mitigate these risks, as it ensures that any lost bait decomposes naturally over time, reducing pollution and safeguarding marine habitats. The adoption of artificial bait also contributes to more sustainable fishing practices by enabling selective fishing and reducing bycatch. Artificial bait can be designed to attract specific species, minimizing the capture of non-target species and helping fishers comply with regulations aimed at protecting vulnerable populations [16]. These advantages make artificial bait an important tool for promoting environmental responsibility within the fishing industry.

Recent advancements in artificial bait design, such as the integration of fluorescent coatings, scent-mimicking compounds, and

aerodynamic shapes, have further improved their functionality. Fluorescent coatings enhance visibility in various water conditions, particularly in deeper or turbid environments, making baits more detectable to fish **[17,18]**. However, their effectiveness is highly context-dependent, varying with water clarity, light conditions, and species-specific visual preferences [19]. Similarly, scent-mimicking compounds replicate the olfactory cues of natural bait, which are critical for attracting fish species that rely heavily on smell for foraging [20]. Despite their potential, these compounds often fail to fully replicate the complex chemical signals of live bait, which include pheromones and other organic cues critical for eliciting feeding responses [21], [22]. Moreover, concerns about unintended consequences, such as increased hooking injuries or altered fish behavior, necessitate careful evaluation of their ecological impacts [23]

Aerodynamic shapes in artificial bait are another significant innovation, improving hydrodynamic performance by reducing drag and allowing more realistic movement in water **[6],[24]**. Such designs are particularly effective in dynamic aquatic environments where water currents play a significant role in bait visibility and movement [4]. However, like other features, their success depends on the specific environmental and fishing conditions, as factors such as salinity, temperature, and the presence of competing natural prey influence their overall effectiveness [13], [25]

While artificial bait excels in durability, cost efficiency, and adaptability, natural bait retains advantages in sensory and aromatic appeal, particularly in fisheries targeting species with strong olfactory and gustatory preferences [26] [27]. Studies comparing artificial and natural bait consistently highlight the latter's ability to attract fish more reliably in certain contexts, especially when fish are accustomed to specific prey [28], [29]. However, the sustainability benefits of artificial bait are undeniable. By reducing pressure on natural bait stocks, artificial bait contributes to ecosystem stability and minimizes the ecological footprint of fishing practices [30] [31]

The choice of bait color and size is another critical factor influencing fishing success. Fluorescent and medium-sized baits often prove effective, as they align with the visual and predatory preferences of many target species [17],[19]. However, optimal bait characteristics can vary significantly depending on species and environmental conditions, necessitating a tailored approach to bait selection [22], [27].

Finally, the development of biodegradable and eco-friendly materials is essential to address concerns about marine pollution and the environmental costs of artificial bait production. Non-biodegradable baits contribute to plastic waste, posing risks to marine ecosystems if lost or discarded during fishing operations [32], [12]. Transitioning to biodegradable materials can mitigate these issues, ensuring that artificial bait supports not only economic and operational efficiency but also long-term ecological sustainability [31], [33].

In summary, artificial bait, supported by material and design innovations, offers a viable pathway to reducing dependence on natural bait while promoting sustainable fishing practices. However, further refinement is needed to optimize sensory mimicry and environmental adaptability, ensuring that artificial bait can effectively replace natural bait across diverse fisheries.

IV. CONCLUSION

The use of artificial bait made from composite resin and aluminum presents a promising alternative to address the limitations associated with natural bait in tuna fisheries. These materials offer unique advantages, with composite resin providing flexibility in design and the ability to replicate natural prey movements, while aluminum contributes to durability and resistance against harsh marine conditions. Innovations in artificial bait design, such as the integration of fluorescent coatings and biodegradable materials, further enhance their effectiveness and sustainability. These advancements not only reduce reliance on increasingly scarce natural bait stocks but also minimize ecological impacts by promoting environmentally friendly fishing practices. Despite the clear potential of artificial bait, challenges remain in optimizing their performance across varied marine environments and target species. While artificial bait demonstrates high durability and cost-effectiveness, its sensory and visual appeal must be continually refined to match the effectiveness of natural bait in attracting target fish. Additionally, understanding the long-term ecological impacts of artificial bait on marine ecosystems requires further research to ensure these solutions are both sustainable and practical for widespread adoption. Future studies should focus on enhancing the hydrodynamic properties and adaptability of artificial bait to diverse environmental conditions while exploring new materials that balance durability with eco-friendliness. Collaboration between researchers, fisheries, and policymakers is crucial to developing artificial bait technologies that meet the demands of both economic feasibility and ecological

responsibility. In conclusion, artificial bait offers a viable pathway toward sustainable tuna fisheries. By leveraging material innovations and strategic design improvements, artificial bait can support the transition to more environmentally conscious practices, ensuring the long-term viability of tuna fisheries while safeguarding marine ecosystems.

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