A Comparison of Microplastic in Fish From Australia and Fiji

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Awareness surrounding plastic pollution has increased significantly in the past decade, leading to concerns on potential adverse effects on biota, including the consumption of microplastic by fish. Globally, plastic has been found in many species of fish, but little research has been undertaken in the southern hemisphere. We assessed the abundance and type of plastic in fish captured and sold for human consumption in Australia and Fiji. Fish (goatfish, sea mullet, paddletail, and common coral trout) had their gastrointestinal tracts dissected and microplastic quantified under a microscope. Plastic polymer types were confirmed using μ-FTIR. In Australia, plastic was found in 61.6% of fish gastrointestinal tracts, while in Fiji, 35.3% of fish had plastic. Fish from Australia had almost double the amount of plastic on average than fish caught in Fiji, with 1.58 (± 0.23) pieces per fish in Australia compared to 0.86 (± 0.14) in fish caught in Fiji. The types of plastic differed between countries, with fibers comprising 83.6% of microplastic pieces in fish from Australia whereas 50% of microplastic found in fish from Fiji was film. Polyolefin was the most abundant polymer type in both fibers from Australia and film from Fiji. We hypothesize variations in abundance and plastic type are a reflection of the population density and coastal geomorphology, but may also be a result of legislation and waste management strategies in the two countries. This work adds evidence to the pervasive presence of plastic in fish gastrointestinal tracts, reinforcing the urgent need for efficient plastic waste management, but also a better understanding of the impacts of microplastic on marine biota.

Keywords: microplastic, ingestion, fish research, South Pacific, plastic pollution, contamination

INTRODUCTION

Plastic debris is accumulating in marine environments at a rapid rate, with recent research finding plastic to be ubiquitous in oceans globally (Barnes et al., 2009; Wilcox et al., 2015; Worm et al., 2017). Plastics are highlighted as a major environmental hazard and can have a variety of health impacts on marine organisms, including suffocation, entanglement and contamination throughout all trophic levels (Page et al., 2004; Pierce et al., 2004; Stamper et al., 2009; Rochman et al., 2013). A highly prevalent type of plastic in the environment are microplastic, which are defined as pieces of plastic less than 5 mm in size (Eriksen et al., 2014; da Costa et al., 2016). Microplastic is either manufactured to be this size (primary microplastic) or the result of environmental weathering and forces breaking down pieces of larger plastic (secondary microplastic) (Worm et al., 2017). Recently, there has been a rise in research surrounding microplastic as an environmental contaminant, initiated by an increase in concern and awareness from the scientific community, policymakers and the general public on the impacts these small particles are having on marine environments

and biota (Rochman et al., 2013). Studies have now found microplastic in all areas of the water column, including deep-sea floors, coastal sediments and the ocean surface (Reisser et al., 2013; Eriksen et al., 2014; Peng et al., 2018). Furthermore, they have been identified to be ingested by a range of marine organisms, including whales, fish and larvae (Besseling et al., 2015; Steer et al., 2017; Burkhardt-Holm and N'Guyen, 2019).

Microplastic ingestion in marine fish is well documented (Markic et al., 2019; Sequeira et al., 2020; Savoca et al., 2021), with field studies reporting microplastic ingestion in wild-caught fish of both commercial and non-commercial interest from a broad range of trophic levels, habitats and benthic zones (Foekema et al., 2013; Nadal et al., 2016; Murphy et al., 2017; Baalkhuyur et al., 2018; Burkhardt-Holm and N'Guyen, 2019; Garnier et al., 2019). Despite this, the literature surrounding microplastic in fish sold through seafood markets and supermarkets is limited. With seafood consumption increasing worldwide, understanding the potential risks of human consumption of microplastic needs further attention. Apart from the reported physical impacts of microplastic when ingested by marine organisms (Wright et al., 2013), there is also concern that the small particles could act as a vector for toxic chemicals either added during manufacturing stages, or pollutants [e.g., persistent organic pollutants (POPs), flame retardants and heavy metals] sorbed onto the surface of the microplastic (Teuten et al., 2009; Bakir et al., 2014). Laboratory observations show these chemicals are capable of causing adverse impacts on fish (e.g., Rochman et al., 2014; Pedà et al., 2016), however, the extent to which microplastic ingestion is exposing individuals to chemical pollutants or its potential implications to seafood safety is far from well understood (Hermabessiere et al., 2017; Hantoro et al., 2019; Walkinshaw et al., 2020).

Land-based activities, such as unprotected landfill, mismanagement of household and commercial waste, sewage, littering, and industrial pollution are major sources of marine plastic (Jambeck et al., 2015; Li et al., 2016; Turrell, 2020). Therefore, to some extent the plastic found in the ocean is a reflection of the waste produced and how it is managed in different countries. Australia and Fiji have different waste management strategies, as well as differing population sizes, cultures, and lifestyles. Marine litter generation is predicted to be high in countries that have under-performing waste management systems. Small Island Developing States (SIDS), such as Fiji, have unique problems in waste collection and disposal due to their lack of space for landfill, inadequate expertise and technology and particularly their remote locations creating exhaustive costs to transport waste and recycling (Mohee et al., 2015). Furthermore, Fiji's increase in urbanization alongside growth in tourism have amplified the imbalance between the abundance of waste produced and the country's ability to manage it correctly (Kelman and West, 2009; Lachmann et al., 2017). Although Jambeck et al. (2015) estimated that Australia produces over eleven times the amount of plastic waste that Fiji does (1,902,591 kg per day compared to 168,430 kg per day in 2010), the amount of mismanaged waste in Fiji is almost four times that of Australia (13,889 tonnes in Australia compared to 49,257 tonnes in Fiji) (Jambeck et al., 2015).

In this study, we investigate the abundance and type of plastic found in the gastrointestinal tracts of a suite of species of fish captured and sold for human consumption in two regions of the South Pacific (Australia and Fiji) with distinct economic development levels and waste management strategies. In doing so, we provide essential information on microplastic contamination in fish from a vastly understudied region (Markic et al., 2019; Savoca et al., 2021), which can be used as key baseline data for future studies to monitor the presence and patterns in microplastic type and abundance in the South Pacific. Overall, the extent of microplastic contamination in commercially sold fish from the South Pacific is unknown, as are the types of plastics and polymers present, and how they compare among different sized countries, regarding landmass, population, economy and waste management strategies.

MATERIALS AND METHODS

Sample Collection
Fish samples (193 total) from five species of commercially important species were collected from fish markets in Suva, Fiji, and Brisbane and Sydney, Australia in 2019 (**Figure 1**). Fish were selected based on local availability, as well as covering a range of trophic levels and habitats (e.g., reef-associated, benthic, pelagic) (**Table 1**). Three species were collected in both countries (common coral trout, paddletail, sea mullet), the other species were closely related (Family Mullidae) and chosen based on similarity in feeding habits, habitats and trophic levels. All 73 fish (∼20 individuals from 4 species) purchased in Australia were from the same commercial fishing areas in Queensland and were purchased in June 2019. In Fiji, 120 fish (∼30 individuals from 4 species, see **Table 1**) were purchased from the Suva Municipal Markets in February and March 2019. All fish were locally fished. Most fish were purchased whole, although some samples (eight coral trout from Australia) were collected as frames, with the gastrointestinal tracts still intact, following filleting for human consumption. All fish were transported on ice to the laboratory and stored in the freezer at –20°C until further processing.

Laboratory Methods
All processing of fish occurred inside a laminar flow cabinet. Fork length of the whole fish or fish frame was measured (**Table 1**). The fish were rinsed with ultrapure (Milli-Q) water, dissected, and the gastrointestinal tracts removed. The fish that were collected as frames had the outside rinsed thoroughly with ultrapure water to ensure any external contamination was removed. The entire gastrointestinal tracts were weighed, rinsed in ultrapure water, and placed in individual previously cleaned polypropylene sample jars (**Table 1**). Due to interstate travel restrictions, dissections of some species (common coral trout, sea mullet, paddletail) from Queensland occurred in the field, under open airflow, and all surfaces cleaned thoroughly. In these cases, dissected gastrointestinal tracts were rinsed with ultrapure water, stored and sealed in previously cleaned vials, and transported to the laboratory until further processing, as described above.
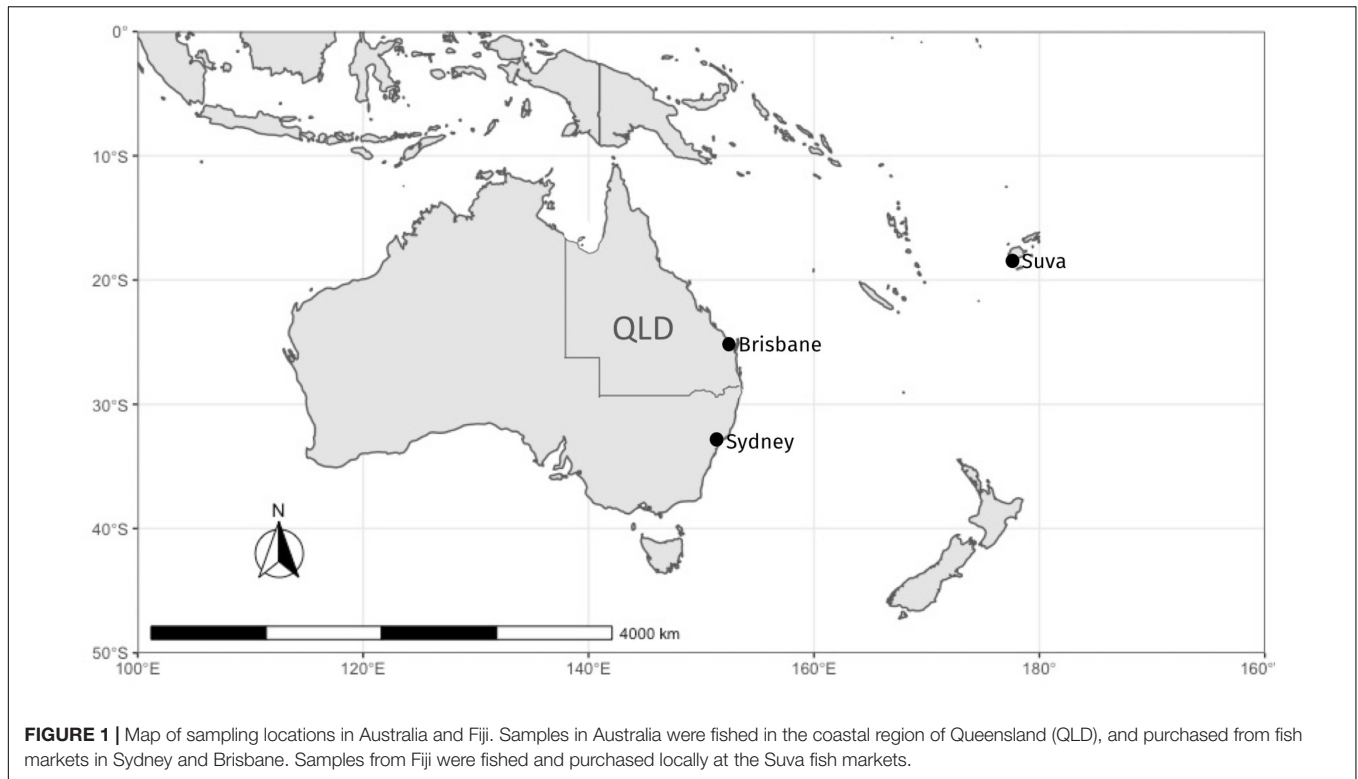
FIGURE 1 | Map of sampling locations in Australia and Fiji. Samples in Australia were fished in the coastal region of Queensland (QLD), and purchased from fish markets in Sydney and Brisbane. Samples from Fiji were fished and purchased locally at the Suva fish markets.

TABLE 1 | Fish purchased in Australia and Fiji.

Common name	Scientific name	Feeding strategy	Habitat	Australia fork length	Fiji fork length	Australia gastrointestinal tract weight	Fiji gastrointestinal tract weight
Common coral trout	*Plectropomus leopardus*	Carnivore	Reef-associated	468.9 (± 18.1)	308.8 (± 8.8)	45.1 (± 5.1)	20.4 (± 2.8)
Bluestriped goatfish	*Upeneichthys lineatus*	Carnivore	Demersal	159.8 (± 5.2)		2.7 (± 0.24)	
Paddletail	*Lutjanus gibbus*	Carnivore	Benthopelagic	430.8 (± 8.5)	214.5 (± 3.5)	39.3 (± 4.8)	9.9 (± 0.65)
Yellowspot goatfish	*Parupeneus indicus*	Carnivore	Demersal		254.5 (± 3.3)		12.6 (± 0.6)
Sea mullet	*Mugil cephalus*	Detrivore	Benthopelagic	343.8 (± 5.6)	245.0 (± 2.2)	24.8 (± 7.7)	13.9 (± 1.8)

The table shows the common name, scientific name, feeding strategy, habitat, mean fork length (mm ± SE), and mean gastrointestinal tract weight (grams ± SE) of each fish species from each country.

Organic material in the gastrointestinal tracts was digested with 10% potassium hydroxide (KOH) solution in ultrapure water (Foekema et al., 2013; Rochman et al., 2015). The samples were then left to digest in closed vials overnight at 60°C in an oven. The digestion method using 10% KOH has been documented as the best method to extract microplastics with the highest isolation efficiency (Dehaut et al., 2016; Lusher et al., 2017; Thiele et al., 2019).

The resultant liquified samples were sieved through two sieves (1 mm and 38 μm), catching any hard objects, including microplastic. All of the sieving process was completed in the laminar flow cabinet. The sieves were examined under a stereo microscope (Leica M80) and any objects thought to be plastic were recorded and collected for further chemical analysis. Microplastic color, size group (>38 μm and <1 mm or >1 mm) and type (i.e., fibers, fragments or film; **Figure 2**) were all recorded.

Contamination Controls

All surfaces, vials and utensils were cleaned beforehand with ultrapure water and dried in a laminar flow. Throughout all processing and analysis, strict protocols were undertaken to ensure that contamination risk was minimized (Lusher et al., 2017; Provencher et al., 2017; Hermsen et al., 2018). The laboratory work area was cleaned methodically before dissections occurred, and between each fish. All fish were rinsed and dissections performed in a laminar flow cabinet to avoid external contamination. Bright pink lab coats and clothing made from natural fibers were worn at all times. Only two pink fibers were found in the samples, and they were excluded. Both procedural and environmental blank samples were prepared during every stage of the methodology (open vials during dissection, polypropylene jars with 10% KOH during digestion and open Petri dishes during sieving and microscope analysis) (Hermsen et al., 2017; Kroon F. et al., 2018). Blank samples
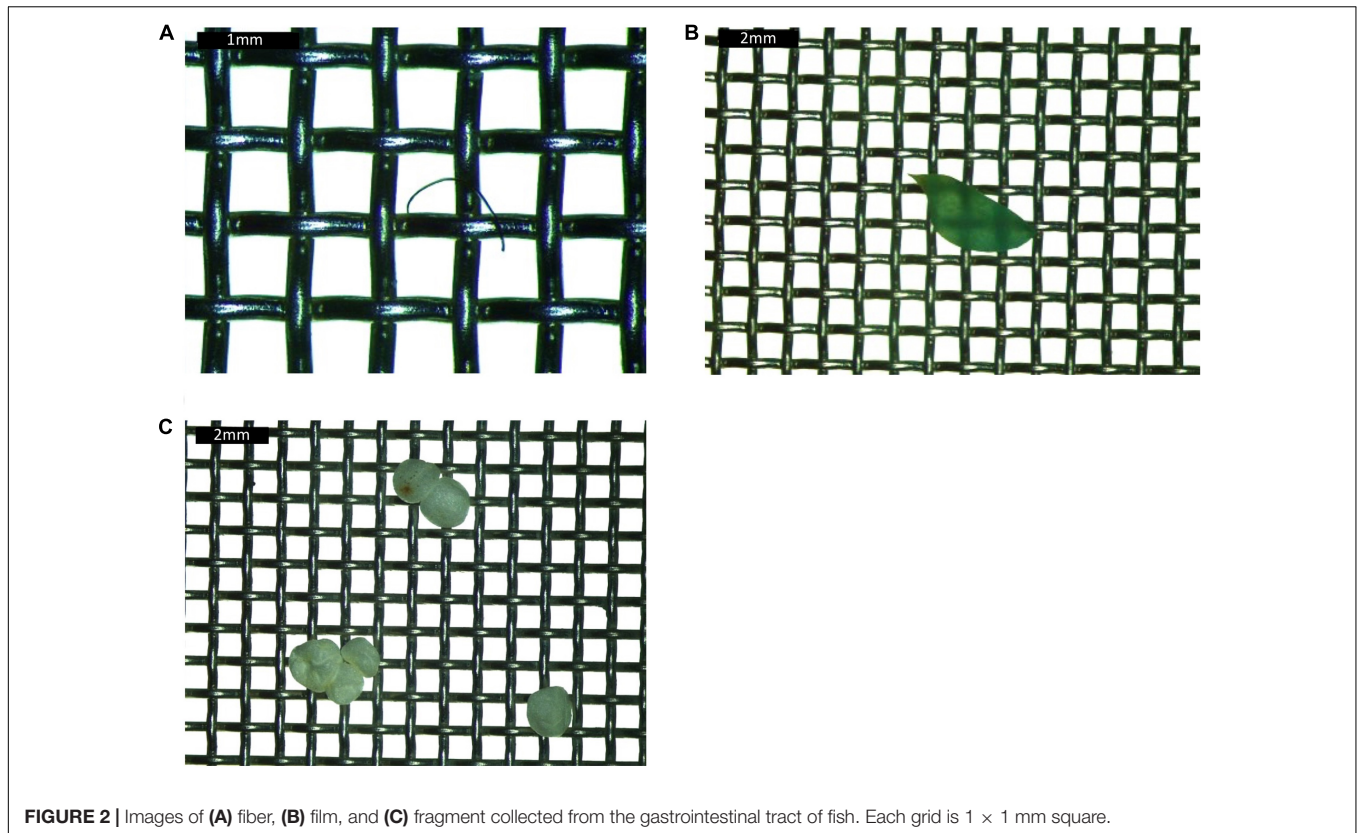
FIGURE 2 | Images of **(A)** fiber, **(B)** film, and **(C)** fragment collected from the gastrointestinal tract of fish. Each grid is 1 × 1 mm square.

were placed directly alongside the work area and processed, filtered and analyzed using the same methods we used for fish gastrointestinal tracts. No evidence of contamination was found in the blank samples.

Characterization and Identification of Microplastics

We tested microplastic pieces using micro-Fourier Transformed Infrared Spectroscopy (μ-FTIR) (Bruker Hyperion) to identify polymer type (Jung et al., 2018). Attenuated Total Reflection (ATR) was applied to all cleaned samples at a resolution of 4 cm^{-1}. Aperture size was readjusted to as small as necessary depending on sample size. Three randomly selected measurement positions were chosen within each sample, and 64 co-scans for each measurement were taken. The spectrum range was set between 3,900 and 650 cm^{-1}, with the atmospheric water/CO_2 region between 2,500 and 1,900 cm^{-1} excluded when compared to spectral libraries, as recommended by Primpke et al. (2018) and Jensen et al. (2019). All spectra outputs were compared to the libraries of reference (Bruker ATR Library for Polymers, Bruker ATR Library for Chemicals, Bruker ATR Library for Pharma, Bruker ATR Library for Forensics) to verify the polymer type (**Supplementary Figure 1**). A hit quality value (i.e., percent match) between the sample and the library reference spectrum was obtained for each item. The polymer was only confirmed if the match was > 50% and additionally if the stringent visual analysis of the peaks were identified as the same.

We aimed to test all pieces of microplastic, however, some pieces were too small to analyze on the μ-FTIR slide (24% of all samples) so we did not include these in our final plastic counts. When there were multiple pieces of microplastic from the same fish that visually appeared to be the same plastic piece and polymer type, we tested a portion of the pieces first (e.g., if there were three pieces of plastic that visually appeared the same we would test two of them). If polymer type was found to be the same, we assumed that the remaining pieces were of the same polymer type.

Data Interpretation and Statistical Analysis

The color, type and size of microplastics were quantified for each individual fish. The average amount of microplastic per fish of each species and country was calculated; this is referred to as the plastic load (PL). This value includes all fish sampled, even those which were found to have no plastic present, hence the average PL can be a value less than one. The percentage of fish with at least one piece of plastic was quantified for each species and country. This value represents the frequency of occurrence of plastic ingestion (FO).

We tested for a relationship between plastic load and fork length or gastrointestinal tract weight but none were found. The data were analyzed using a negative binomial generalised linear model (GLM) to investigate the influence of location of capture (country) and species on the estimated frequency of occurrence of

plastic and plastic load per fish. We used the Akaike's information criterion value corrected for small sample sizes (AICc) to select the best model fit. For the best fit model (Location + Species), estimates of the species means were made, followed by ANOVA and pairwise tests to determine any differences between species and countries. Residual plots were analyzed to ensure data met assumptions. Graphical outputs were produced from the model predictions. Statistical analyses were conducted using R studio software (Version 3.6.1), including the maps (Becker et al., 2018), ggplot2 (Wickham, 2016), emmeans (Length et al., 2020), doBy (Højsgaard and Halekoh, 2020), rgeos (Bivand and Rundel, 2020), rnaturalearth (South, 2017a), rnaturalearthdata (South, 2017b), sf (Pebesma, 2018), treemap (Tennekes, 2017), tidyverse (Wickham et al., 2019), and sunburstR (Bostock et al., 2020) packages.

Subsequently, Primer-e was used to run Canonical Analysis of Principal Coordinates (CAP) on the multivariate polymer dataset. CAP was used to assess the ability to classify fish to their country of origin based on the types of microplastic they contain. CAP is a constrained ordination that allows an unbiased measure of how different groups are in multivariate space (Anderson and Willis, 2003). Variables were $\log(x + 1)$ transformed and unrestricted random permutations of the transformed data were applied. Cross-validated classification accuracies were analyzed for all species combined.

RESULTS

Differences in Abundance of Plastic Between Countries

A total of 296 pieces of microplastic were collected using visual microscope techniques (148 from Fiji and 148 from Australia), of which 212 were confirmed as microplastic using the μ-FTIR (102 from Fiji and 110 from Australia). The majority of microplastic pieces were larger than 1 mm in size (88.9% of pieces from Australia and 86.4% of pieces from Fiji), with the remainder of pieces being between 38 μm and 1 mm.

There were no trends between fish size, or the weight of the gastrointestinal tract, and the amount of microplastic counted. Overall, the frequency of occurrence of plastic ingestion in fish from Australia was higher than Fiji (61.6% in Australia compared to 35.3% in Fiji) and there was a significant difference between countries ($p < 0.001$, **Figure 3**). The overall plastic load found in fish was higher in Australia compared to Fiji (1.58 ± 0.23 and 0.86 ± 0.14 pieces per fish, respectively) ($p < 0.05$). Both countries had a large percentage of fish (38.4% in Australia and 64.7% in Fiji) that had zero pieces of microplastic (**Figures 3A,B**). The highest number of microplastic found in any one fish was eight pieces, found in a common coral trout and paddletail in Australia, and a common coral trout from Fiji (**Figures 3A,B**, respectively).

All species from both countries had microplastic present, however, the predicted frequency of occurrence of plastic ingestion varied depending on the species and which location they were captured (**Figure 4**). In Fiji, the common coral trout was the species with the most fish with at least one piece of plastic, whilst yellowspot goatfish had the least (**Figure 4**). In Australia,

the paddletail had the most fish with microplastic and the sea mullet had the least (**Figure 4**).

The plastic load also changed between species and locations. In Fiji, the highest expected microplastic load was in paddletail and the lowest in sea mullet (**Figure 5**), whereas, in Australia, common coral trout had the most pieces of microplastic on average in their gastrointestinal tract and similarly to Fiji, sea mullet had the least (**Figure 5**).
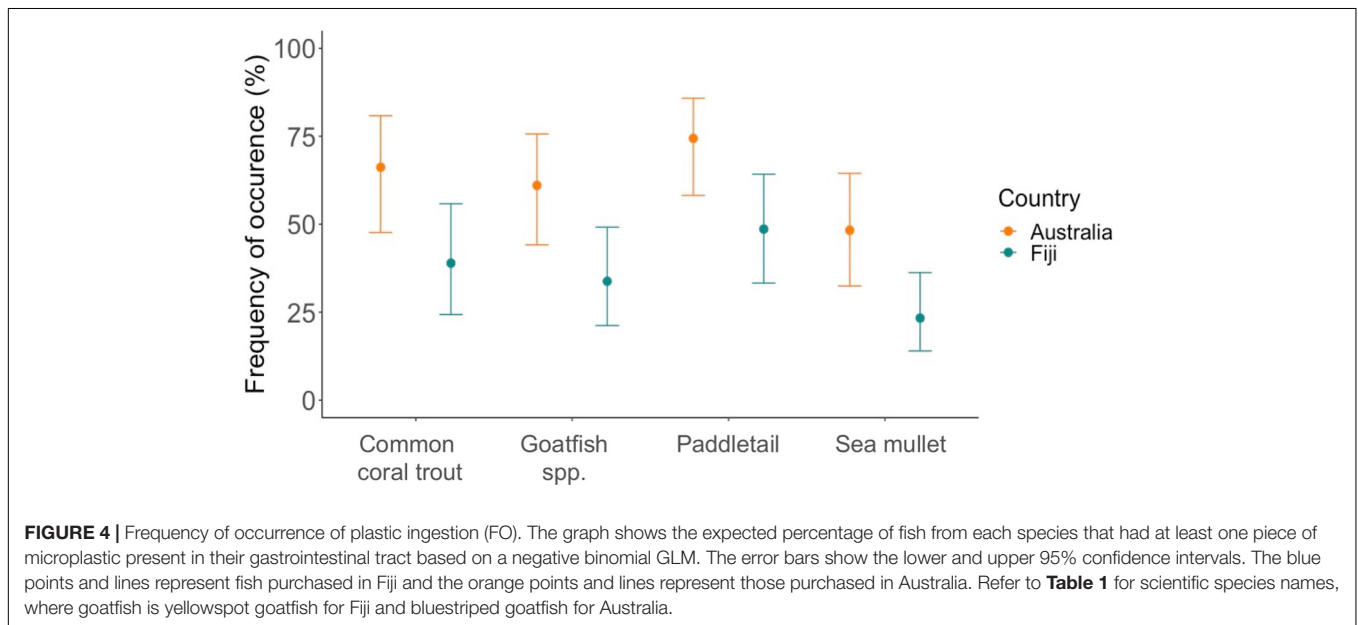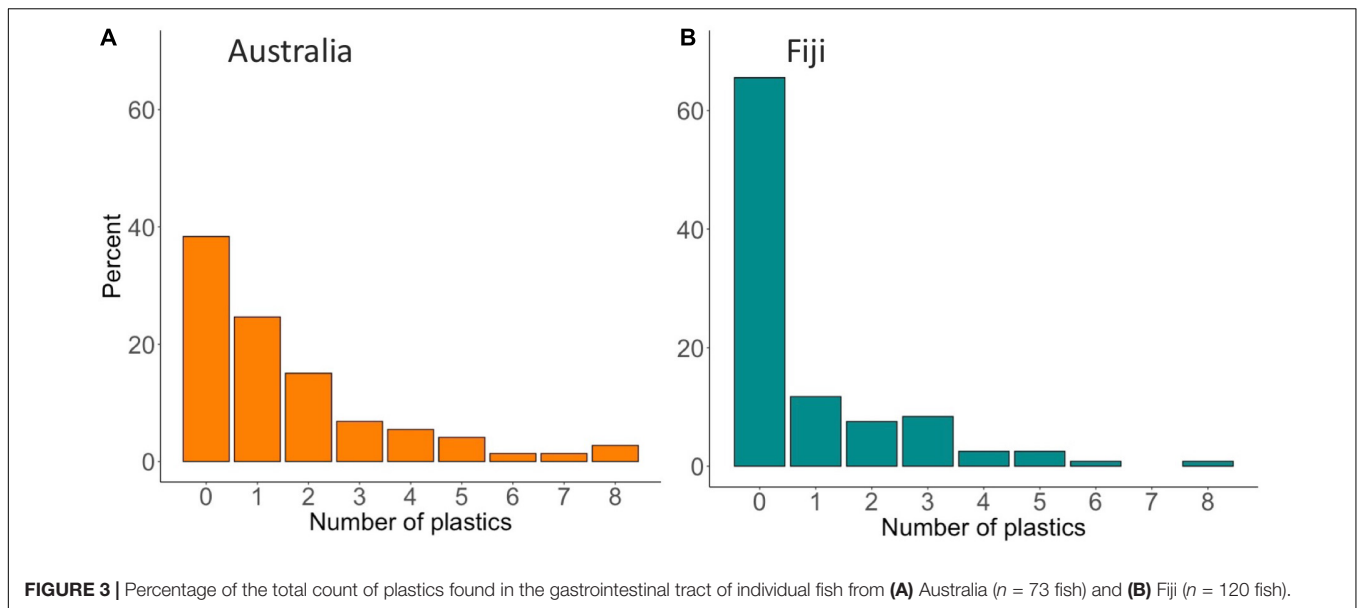
Differences in Types of Plastic Between Countries

Of the 296 pieces initially identified under the microscope as microplastic, we analyzed 124 pieces using the μ-FTIR (**Figure 5**). This number of analyses in the μ-FTIR is due to, first, some pieces of microplastic being too small (e.g., not visible to the naked eye) and thus we were unable to transfer and verify their polymers onto the μ-FTIR slide, with these pieces removed from the reported total counts of plastic ($n = 71$). Second, when multiple pieces of plastic in the same fish visually appeared identical we tested a portion of microplastic pieces, with the μ-FTIR confirming these pieces were all the same polymer. Overall, of the 124 pieces we tested, 111 were confirmed as microplastic, an 89.5% accuracy. After the pieces of plastic that were visually identified, and confirmed by the μ-FTIR as being the same were combined back into our total ($n = 101$), we had a total of 212 confirmed pieces of microplastic.

There were differences in the types of microplastic found in fish between the two countries. Half of the microplastics found from fish in Fiji were film (50.0%), with the remaining split between fragments (25.5%) and fibers (24.5%) (**Figure 6A**). In contrast, in Australia, fibers dominated (82.4%), with fewer fragments (10.2%) and film (7.4%) present (**Figure 6B**).

The polymer type of plastic pieces varied between countries and within the type of microplastic (fiber, fragment and film, **Figure 6**). In fish from Australia, pieces of microplastic were dominated by polyolefin (48.2% of all fibers, film and fragments from Australia; **Figure 6A**). Polyolefins are a broad polymer group that includes polyethylene (75% of all Australian polyolefins), ethylene-vinyl acetate (11%), synthetic rubber (5.5%), polypropylene (5.5%), and polystyrene (3%) (see **Supplementary Table 1**). In fish from Fiji, polyolefin was also the most abundant polymer group identified, with 38% of all plastic falling in this category. This included polyethylene (36% of Fiji polyolefins), ethylene-vinyl acetate (26%), polypropylene (15%), polystyrene (10%), and other polymers such as polyurethane and synthetic rubber (**Supplementary Table 1**).

Within the fiber morphotype, polyolefin fibers (49.5% of all Australian fibers) were the most prominent, followed by polyester with 20% (**Figure 6A** and **Supplementary Table 1**). Synthetic fibers (10.1% of Australian fibers), were also substantial and were composed of a combination of elastane, lycra, rayon and spandex mixed with natural materials such as cotton and wool. In Fiji, the fibers were dominated by paint (36.0% of fibers from Fiji). Despite this, a total of seven polymer groups were identified in fibers from both countries, with five present in both (pure nylon, paint, polyester, polyolefin and synthetic fiber). Fiji additionally
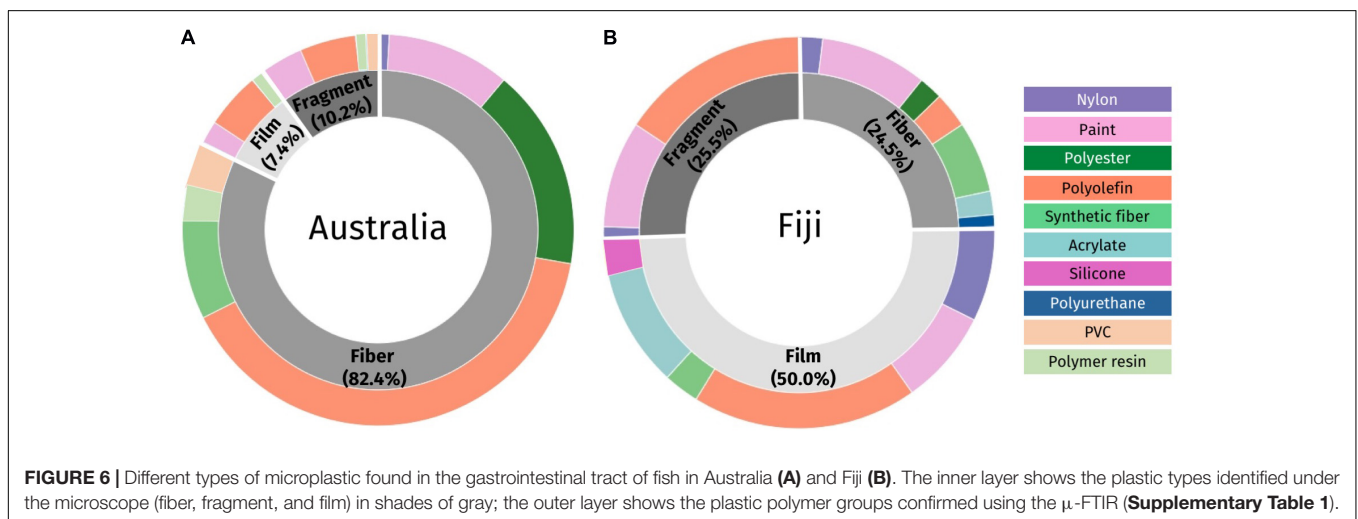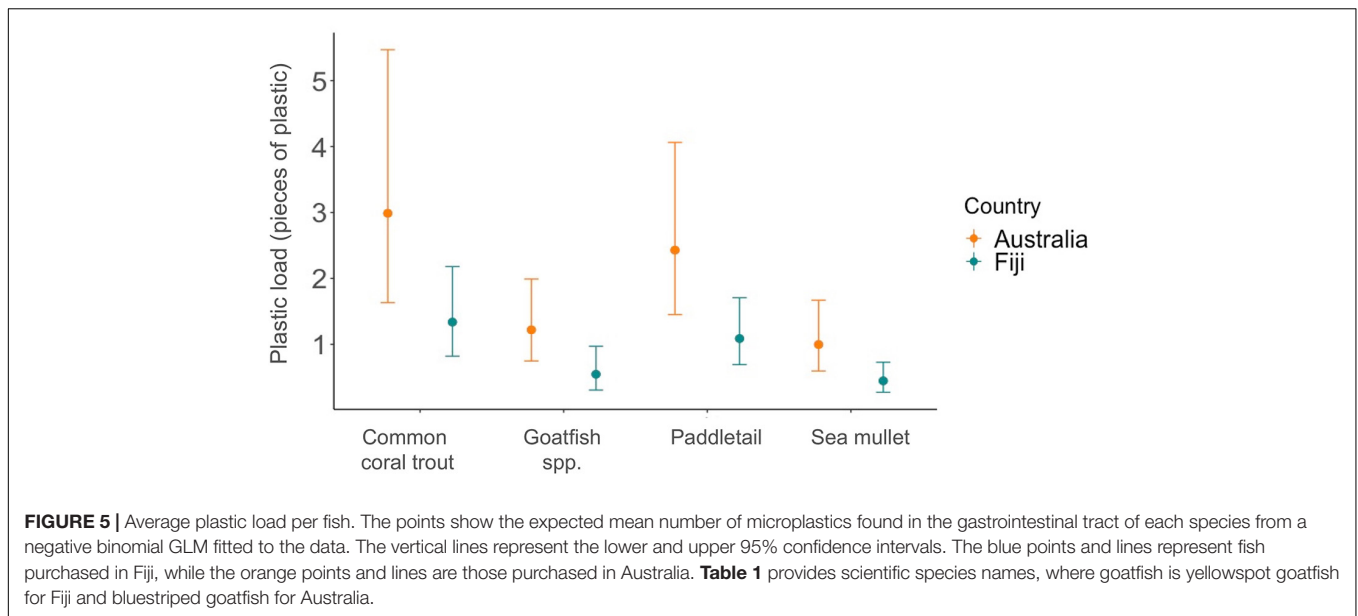
FIGURE 3 | Percentage of the total count of plastics found in the gastrointestinal tract of individual fish from (A) Australia (n = 73 fish) and (B) Fiji (n = 120 fish).

FIGURE 4 | Frequency of occurrence of plastic ingestion (FO). The graph shows the expected percentage of fish from each species that had at least one piece of microplastic present in their gastrointestinal tract based on a negative binomial GLM. The error bars show the lower and upper 95% confidence intervals. The blue points and lines represent fish purchased in Fiji and the orange points and lines represent those purchased in Australia. Refer to **Table 1** for scientific species names, where goatfish is yellowspot goatfish for Fiji and bluestriped goatfish for Australia.

had small numbers of acrylate and polyurethane filaments (n = 2, n = 1, respectively) and Australia had PVC (Poly Vinyl Chloride) and polymer resin filaments identified (n = 4, n = 3, respectively).

In general, film pieces from Australia had less diversity in their polymer types compared to Fiji, with only three polymers identified (**Supplementary Table 1**) while Fiji had six different polymer groups, including polyolefin (37.3%), acrylate (19.6%), paint, nylon, and silicone (**Figure 6B** and **Supplementary Table 1**). Within these six polymer groups there were 14 polymers identified, with polyethylene dominating (24% of all film pieces from Fiji). Fragments were less common in both countries but when present were mostly polyolefin and paint. Additionally, Australia had one piece of both polymer resin and PVC; while Fiji had one piece of nylon.

Results of the CAP analysis revealed an overall high level of accuracy of classification of fish to their country of origin, based on the amount and type of plastic found in their gastrointestinal tracts. Cross-validated classification results varied between countries, with an overall correct classification of 73.96% to the respective country where the fish were caught.

DISCUSSION

All of our five species of fish (*L. gibbus, M. cephalus, P. indicus, P. leopardus, U. lineatus*) consumed microplastic. Overall, 61.6% of fish from Australia and 35.3% of fish from Fiji had microplastic in their gastrointestinal tract contents, with higher average plastic

FIGURE 5 | Average plastic load per fish. The points show the expected mean number of microplastics found in the gastrointestinal tract of each species from a negative binomial GLM fitted to the data. The vertical lines represent the lower and upper 95% confidence intervals. The blue points and lines represent fish purchased in Fiji, while the orange points and lines are those purchased in Australia. **Table 1** provides scientific species names, where goatfish is yellowspot goatfish for Fiji and bluestriped goatfish for Australia.

FIGURE 6 | Different types of microplastic found in the gastrointestinal tract of fish in Australia **(A)** and Fiji **(B)**. The inner layer shows the plastic types identified under the microscope (fiber, fragment, and film) in shades of gray; the outer layer shows the plastic polymer groups confirmed using the µ-FTIR (**Supplementary Table 1**).

loads in Australian (1.58 pieces) fish compared with those from Fiji (0.86 pieces). Microplastic was found in fish species across different trophic levels (carnivores, detrivores) and habitats (reef, seagrass, sediment/sand, open seas, and rocky reef). All five species sampled are important fishery species in both countries, supporting the economy, employment, and food sources of their respective populations. Therefore, quantifying the base levels of microplastic in these species provides leverage for future risk assessment and an understanding of the levels of potential contamination present in seafood to evaluate potential risks to human consumption.

Research on microplastic ingestion in fish from the South Pacific is limited. One of the more recently published studies (Markic et al., 2018), collected fish from markets across four South Pacific countries (New Zealand, Samoa, Tahiti and Rapa Nui), finding that across all regions on average 24.3% of fish ingested plastic, much lower than the 61.6% in our Australian

fish and 35.3% in Fijian fish that we found in our study. The range between countries is broad, but encompasses values similar to those in which we found, with 49.2% of fish from Rapa Nui containing microplastic. Another study investigating fish from a variety of small islands across the South Pacific (Lord Howe Island, French Polynesia and Henderson Island) also found lower numbers of fish with plastic than what our study identified, with Forrest and Hindell (2018) only detecting ten fish from the 126 individuals (7.9%) collected to have microplastic present. Both studies (Forrest and Hindell, 2018; Markic et al., 2018) include species from similar habitats (benthic and rocky reef) to the fishes in our study, however, plastic contamination still varied to our results, with both higher and lower amounts of plastic found in similar species. The only study to our knowledge investigating fish from Fiji found 68% of fish to ingest microplastic, with an average of 5.5 pieces per fish (Ferreira et al., 2020), and these findings are much

higher than what we found in the fish we sampled from Fiji (FO–35.3%, PL–0.86). Research is more prominent in Australia where at least six separate studies have identified microplastic in fish from the region (Cannon et al., 2016; Halstead et al., 2018; Kroon J. F. et al., 2018; Jensen et al., 2019; Su et al., 2019; Crutchett et al., 2020). Kroon J. F. et al. (2018) and Jensen et al. (2019) found much higher levels of contamination than our fish, with both studies finding 95% of fish sampled from the Great Barrier Reef had micro debris present. Clearly, there are discrepancies across currently published data investigating microplastic in fish from the South Pacific; with differences potentially caused by the locations sampled and the waste management from these regions, population sizes of countries, currents and environments retaining or depositing microplastic from offshore, or due to the methodology implemented.

Methods used for detection of microplastic have varied over time, with improvements in technical abilities since microplastic research has increased in popularity (Savoca et al., 2021). Some researchers used only naked-eye (e.g., Forrest and Hindell, 2018) or microscope detection (e.g., Cannon et al., 2016) to visualize the gastrointestinal tract content. Although these methods were initially accepted in microplastic research, the trend in analytical methods are moving toward more robust and standardized laboratory procedures, including a digestion of the gastrointestinal tract content and chemical verification of the polymers (Markic et al., 2019; Savoca et al., 2021). In our study, we ensured we followed the highest standard of methodology, using a chemical digestion, large sample sizes, contamination controls and confirmation of polymers using a chemical verification, such as FTIR (Wesch et al., 2016; Hermsen et al., 2017; Lusher et al., 2017). Although we understand the difficulty with implementing a more complex procedure, particularly in countries were resources are limited, it is likely that previous studies may have underestimated the abundance of microplastic in fish from the South Pacific (e.g., Cannon et al., 2016 where only 0.3% of fish sampled contained microplastic). It is thought that increasing counts of plastic in recent studies is a combination of an improvement in analytical methodology, as well as a likely increase in the fish ingesting plastic more frequently as it becomes more abundant in the environment (Savoca et al., 2021).

Initially, it was predicted that Australia may have less microplastic in fish than Fiji because in recent years Australia has made positive moves forward in its waste management and legislation surrounding plastic use. Specifically, in 2018 the Queensland state government released a comprehensive "Waste Management and Resource Recovery Strategy," including the implementation of "Queensland's Plastic Pollution Reduction Plan"(Queensland Government, 2018a,b). These legislations included the execution of a single-use plastic bag ban, a container deposit scheme, as well as stricter enforcement on illegal dumping and littering (Queensland Government, 2018a). In contrast, in Fiji, waste management strategies are rare, and at the time of sampling the fish in our study, there were no bans on plastic bags, and very limited waste management facilities. In a positive move, there have been recent advances in the management of plastics in Fiji, with a plastic bag ban being enforced at the beginning of 2020, and prohibitions on other plastic items (e.g., Styrofoam and plastic straws) commencing at the start of 2021. With our sampling occurring at the beginning of 2019, these policies had not yet been implemented or had an effect. Despite our initial predictions that Fiji would have higher levels of microplastic in their fish, this was not found to be evident, as overall Australia had both higher frequency of occurrence of plastic ingestion and the plastic load in their fish compared to Fiji. It is likely that neither Australia nor Fiji's recent plans to reduce their plastic output would have had substantive effect on the microplastic presence in such a short time period. Due to the long breakdown time of plastic, the microplastic identified in this study may have been introduced in the environment before the new regulations, nevertheless we expect to see positive effects of these plastic reduction plans over the years and in future assessments. This perpetual microplastic may have been amassing in oceanic accumulation zones, where ocean currents and gyres cause microplastic to gather in particular marine regions. Fish with exposure to these regions are likely to consume more microplastic as a consequence of higher likelihood of microplastic interactions, as well as a limitation to food availability due to the oligotrophic nature of the water (Sigman and Hain, 2012). Although neither Fiji or Australia are located specifically within a microplastic gyre, the currents surrounding both regions suggest high levels of microplastic present in the water, which are likely linked to the microplastic found in fish (Lebreton et al., 2012; Eriksen et al., 2014).

Overall, differences in in population size between the two countries could explain the results, with highly populated coastal regions generally associated with higher densities of plastic debris (Lebreton et al., 2012). Fiji is relatively sparsely populated, with a population size of roughly 900,000, of which around 896,000 live on the coastline (Jambeck et al., 2015). In contrast, in Australia the population is 25 million people, of which 80% reside on the coast (Yang and Kelly, 2015). The east coast, where the fish from this study were caught is particularly dense. The differences in population sizes also mean there is a stark difference in the amount of waste produced each day, with Australia predicted to produce eleven times more plastic waste than Fiji (Jambeck et al., 2015). Land-based effluent discharges are a contributor of microplastic in our waterways, with quality sewage treatment systems acting as a filter to limit their outflow (Siegfried et al., 2017). Depending on the treatment type, one treatment plant in Sydney, on Australia's eastern coast, is thought to discharge between 3.6 and 460 million microplastic pieces into marine systems daily (Ziajahromi et al., 2017). Australia's increase in plastic waste production, as well as land-based effluent discharges, could be influencing the difference in plastic abundance between the countries, however waste management strategies and differing lifestyles could also be having an impact, particularly in the type of plastics identified.

The microplastic found in Fiji fish were dominated by sheets of plastic film, which are commonly secondary microplastic, broken down from original larger pieces of plastic. These could be from a range of sources such as polypropylene or polyethylene (29% of film from Fiji), potentially from plastic bags and soft food packaging, or acrylate and paint chips (also 29% of film

from Fiji) possibly from boats. The issues surrounding waste management strategies in small island developing states such as Fiji could be contributing to this, as incorrect use of landfill and disposal could mean larger plastic items are entering the waterways and subsequently eroded into microplastic (Mohee et al., 2015; Hardesty et al., 2017). In contrast, the landfill management in Australia, as well as legislation, policies and education programs, could be contributing to the lower numbers of fragments and film, as the likelihood of hard or larger pieces of plastic are prevented from entering the ocean in the first place (Willis et al., 2018). In Australia, over 80% of the microplastic identified were fibers, a pervasive microplastic in the marine environment, commonly formed from synthetic clothing and fishing gear (Browne et al., 2011; De Falco et al., 2019). Australia's larger population, as well as the fact that one load of washing may contribute up to 1.5 million pieces of microplastic, may both be contributing to these large numbers of fibers (De Falco et al., 2019). High levels of fibers in fish from developed countries with large populations is evident in other studies. Markic et al. (2018) found New Zealand fish had higher quantities of fibers compared to fish from Samoa, which had more fragments and film. Further, a study from Rochman et al. (2015) comparing fish and bivalves purchased from markets in Indonesia and the United States found that the United States had much larger proportions of microplastic fibers in their fish compared to Indonesia. These comparison studies showing high quantities of fibers in developed countries are noteworthy, and perhaps indicative of a further link between differing lifestyles of populations and environmental plastic contamination.

With global consumption of seafood on the rise, understanding the potential risks and challenges that could transpire from microplastic contamination in seafood is more important than ever (FAO, 2020). The physical and toxicological harm that microplastic could potentially cause to fish and their ecosystems could be a threat to local food security, particularly in communities that rely on seafood as a key source of protein (Béné, 2006; Rochman et al., 2016). The long term exposure of microplastic, and the chemicals associated with them, have the ability to negatively affect fish health, potentially impacting the long term sustainability of fisheries (Smith et al., 2018). The spread of microplastic throughout global marine ecosystems have generated concern about whether microplastic ingestion in seafood could penetrate the food web and eventually be consumed by humans. The fish species sampled in this study are mostly eaten after their gastrointestinal tracts are removed, thus the chance of human consumption of the microplastic in this case is low (Dawson et al., 2021). It is important consumers ensure fish are appropriately gutted prior to consumption. In doing so, they are lowering the risk of microplastic contamination from their diets. However, there is still a potential risk to humans as a result of the uptake and translocation of microplastics and their associated chemicals into the flesh of the fish (Teuten et al., 2009). The mechanisms behind this uptake, and the link between long term exposure of microplastic, and the potential for chemicals to translocate is still understudied, and requires more research effort in the future (Ory et al., 2018; Smith et al., 2018). Furthermore, the risk of consumption of microplastic from a human health perspective is still far from being well understood (Smith et al., 2018; Vethaak and Legler, 2021).

Linking variations in the abundance and type of microplastic present in coastal environments and local biota is an area that requires further investigation. Likewise, understanding the type of plastic present, their location of origin and unraveling the pathways these plastics take to reach the marine environment is crucial to developing solutions for microplastic contamination (Kane and Clare, 2019; Petersen and Hubbart, 2021). While plastic presence across coastal environments is widespread, there are a suite of reasonable intervention points that could help lower its impact, from initial production, to disposal, which would assist in reducing plastic entering the marine environment in the first place (Tibbetts et al., 2018; Prata et al., 2019; Petersen and Hubbart, 2021). By further investigating these avenues, we can begin to create answers to limit the presence of microplastic in marine wildlife and fish species. As yet, we do not yet know how these microplastic may be negatively affecting fish health (Ory et al., 2018), how plastic may be impacting human health or if bioaccumulation and biomagnification of chemicals are occurring (Walkinshaw et al., 2020). However, for now, we can say that fish in the South Pacific are consuming microplastics, and the numbers differ between the two countries. Our results provide important baseline data which can be combined with future data to give a broad picture of microplastic contamination in seafood in the South Pacific.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the animal study because samples were purchased through seafood markets.

AUTHOR CONTRIBUTIONS

NW collected the data, undertook the data analysis, wrote the manuscript, and prepared the figures and tables. BG and PR-S reviewed the manuscript, figures, and tables. BG, PR-S, and MF provided advice and guidance throughout the study. All authors conceived the project idea and designed the data analysis.

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