SAMPAH LAUT

Keberadaan dan Upaya Pengelolaannya di Kota Manado

Markus T. Lasut

LPPM UNSRAT

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KATA PENGANTAR

Saat ini, sampah laut telah menjadi masalah global. Hal ini disebabkan, karena keberadaannya di lingkungan tidak pada tempatnya dan dapat memberikan dampak terhadap ekosistem perairan laut. Di samping itu, diperkirakan, 90% sampah di laut adalah dari bahan plastik. Secara global, jumlah sampah plastik yang mengalir ke laut diperkirakan sebanyak 8 juta ton tiap tahunnya. Oleh karena banyaknya sampah plastik di laut, diperkirakan, hal ini telah memberi dampak buruk bagi hewan laut, seperti burung laut, mamalia laut, kura-kura laut, dan ikan.

Melihat fakta di atas, upaya pemecahan masalah menjadi sangat penting dan mendesak untuk dilakukan. Untuk itu, Perserikatan Bangsa-Bangsa (PBB) menetapkan Hari Lingkungan Hidup Dunia 2018 bertemakan "Pencemaran Plastik" (*plastic pollution*). Indonesia juga telah menyusun rencana aksi, "*the Indonesia's Plan of Action on Marine Plastic Debris 2017-2025*", di mana Indonesia berupaya untuk menurunkan sampah plastik laut (*marine plastic debris*) sebanyak 70% pada tahun 2025.

Dalam upaya mengelola sampah laut di Kota Manado, informasi mengenai keberadaan sampah laut di Teluk Manado, khususnya sampah laut yang terdampar di pantai, dan upaya pengelolaannya disajikan dalam buku ini. Informasi yang disajikan merupakan hasil penelitian dan pemantauan, yang telah dilakukan oleh penulis.

Tujuan dari penulisan buku ini adalah untuk menyajikan informasi tentang hasil penelitian dan pemantauan sampah laut Teluk Manado. Hasil penelitian yang disajikan meliputi kuantifikasi komposisi, kepadatan, dan berat sampah laut, status, dampak, kesadaran lingkungan masyarakat, dan penataan kelembagaan sistem pengelolaan sampah laut di Kota Manado. Hasil pemantauan yang disajikan meliputi pemantauan sampah laut di Teluk Manado pada bulan Agustus dan November 2020.

Informasi yang disajikan dalam buku ini merupakan hasil penelitian dan pemantauan yang dilakukan pada tahun 2019-2020. Kegiatan penelitian tersebut di danai oleh PNBP UNSRAT tahun 2019 dan 2020 melalui skim Riset Dasar Unggulan UNSRAT (RDUU). Sedangkan kegiatan pemantauan didanai oleh Direktorat Pengendalian Pencemaran dan Kerusakan Pesisir dan Laut, Direktorat Jenderal Pengendalian Pencemaran dan Kerusakan Lingkungan, Kementerian

Lingkungan Hidup dan Kehutanan, Republik Indonesia, tahun anggaran 2020.

Buku ini diperuntukkan bagi para peneliti, pemerhati lingkungan, pelaksana pengelolaan lingkungan, dan pengambil keputusan dalam upaya merencanakan kegiatan pengelolaan dalam mengatasi masalah sampah laut. Namun demikian, buku ini bisa menjadi bahan informasi bagi berbagai kalangan, khususnya para pihak dalam bidang pengelolaan lingkungan pesisir dan laut.

Akhirnya, semoga buku ini dapat bermanfaat dan menambah informasi, pengetahuan, dan referensi bagi para pembacanya. Terima kasih.

Manado, September 2021

Markus T. Lasut

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DAFTAR ISI

Bagian I:

HASIL PENELITIAN SAMPAH LAUT DI KOTA MANADO

1

Pendahuluan

DAFTAR ISI

1.1. Latar Belakang

Teluk Manado (TM) merupakan perairan laut yang terletak di bagian Barat Semenanjung Minahasa, pada bagian Utara Pulau Sulawesi. Keberadaan perairan TM sangat erat kaitannya dengan keberadaan Kota Manado. Limbah (cair dan padat) masuk ke perairan ini melalui 5 sungai yang melintasi kota. Limbah cair, yang masuk tanpa mengalami pengolahan terlebih dahulu, telah menyebabkan penurunan kualitas air di daerah muara sungai dan pesisir (Lasut *et al.*, 2005; Lasut *et al.*, 2008; Lasut *et al.*, 2017). Limbah padat (sampah), yang memenuhi sungai, masuk ke perairan laut TM (Lasut *et al.*, 2008); akibatnya, sampah tersebut, yang secara umum disebut sebagai sampah laut (*marine litter*) karena keberadaannya di laut (Cheshire *et al.*, 2009; Lippiatt *et al.*, 2013; EEA, 2015; Anonimus, 2017; Lott *et al.*, 2020; Lott *et al.*, 2021), telah menjadi satu dari sekian permasalahan dalam pengelolaan daerah penyelaman di Taman Nasional Bunaken (Lasut *et al.*, 2017), bahkan di seluruh Perairan TM.

Hasil penelitian yang telah dilakukan pada tahun 2019 (Lasut *et al.*, 2020) menunjukkan, bahwa ditemukan 9 jenis bahan sampah laut yang ada di TM di mana didominasi oleh sampah plastik (> 30%); dan hal ini mengalami peningkatan yang signifikan sejak tahun 2017. Hal ini sangat berhubungan dengan situasi dan kondisi di daerah daratan Kota Manado (Lasut *et al.*, 2020). Kondisi sampah laut tersebut dapat memberi dampak buruk bagi ekosistem TM (Lippiatt *et al.*, 2013, Debrot *et al.*, 2013; Pane *et al.*, 2020; Girard *et al.*, 2021).

Berbagai dampak negatif telah terjadi yang disebabkan oleh sampah laut (*marine litter*) di TM, di antaranya, yaitu ditemukannya potongan plastik yang besar di perairan sekitar TM oleh Green Eye project Aquamarine Fukushima, Jepang, pada tahun 2011 (Lasut *et al.*, 2018); ditemukannya potongan plastik di dalam perut ikan 'raja laut', *living fossil*, *Latimeria menadoensis* (Lasut *et al.*, 2018). Hal ini dapat memberikan kerugian yang besar bagi masyarakat karena sumber daya perikanan dari TM dapat terganggu.

Oleh karena dampak negatif tersebut di atas, maka kegiatan mitigasi dampak sampah laut (*marine litter*) di perairan TM dalam upaya perbaikan lingkungan perairan laut sangat perlu (*urgent*) dilakukan. Apabila dilakukan, maka kegiatan ini akan menjadi bagian penting dari kegiatan pengelolaan sampah laut, khususnya dalam upaya untuk mendukung komitmen Pemerintah Indonesia dalam mengurangi sampah plastik di laut sebesar 70% sampai dengan tahun 2025 (Anonimus, 2017; GRI, 2017).

1.2. Permasalahan sampah laut

Sampah telah menjadi masalah global, karena berada di mana-mana dan menimbulkan dampak bagi lingkungan, baik sampah yang terdapat di daratan maupun di lautan (Debrot *et al.*, 2013; Lasut *et al.*, 2018; Liu *et al.*, 2013; Smith dan Markic, 2013; da Silva *et al.*, 2016; Lott *et al.*, 2020; Pane *et al.*, 2021; Girard *et al.*, 2021). Sampah laut, yang merupakan limbah padat dari daratan dari aktifitas manusia, masuk ke lingkungan laut melalui sungai-sungai, saluran drainase kota, atau dibawa oleh pengunjung ke pantai (Derraik, 2002; Sheavly, 2010), dan keberadaannya dipengaruhi oleh kegiatan pengelolaan sampah di darat (Liu *et al.*, 2013; Lasut *et al.*, 2018). Dampak dari sampah laut ini sangat berbahaya bagi sumber daya dan ekosistem perairan, ekonomi, dan sosial (Lippiatt *et al.*, 2013; Debrot, 2013).

Perairan laut di wilayah Asia Tenggara, khususnya di wilayah segitiga karang dunia (*world coral triangle area/*CT), di mana bagian pusatnya berada di perairan laut Indonesia, dikenal sangat kaya akan keanekaragaman hayati laut. Oleh karena itu, perairan laut Indonesia sering disebut sebagai *world marine mega-biodiversity* dan *Amazon of the Ocean* (Anonimus, 2017). Namun, saat ini, daerah perairan laut ini sedang mengalami tekanan yang sangat tinggi, bahkan berpotensi menimbulkan risiko yang besar, dari pencemaran sampah plastik (*marine plastic debris*), yang dapat menyebabkan habitat dan keanekaragaman biota menurun dan punah, serta kualitas lingkungan dan kuantitas sumber daya pesisir dan laut menurun. Kondisi perairan laut yang penuh dengan sampah plastik dapat ditemukan di beberapa daerah di dalam wilayah CT di perairan Indonesia, misalnya di Bali, Kupang, Ternate, dan Manado; namun, kondisi seperti itu juga ditemukan di daerah perairan di negara lain (misalnya: Papua Nugini) di wilayah CT (Naatonis, 2010; Wardi, 2011; Smith, 2012; Siregar, 2014; Sahil *et al.*, 2016; Lasut *et al.*, 2018).

Indonesia berperan penting dalam keberadaan wilayah perairan laut CT; namun, bersamaan dengan itu, Indonesia dikenal juga sebagai pencemar sampah plastik nomor 2 terbesar di dunia, yang diperkirakan menghasilkan sampah plastik 3,22 juta ton pada tahun 2010 (Jambeck *et al.*, 2015) dan meningkat menjadi 4,3 juta ton pada tahun 2016 (Law *et al.*, 2020). Hal ini bisa saja terjadi karena dipicu oleh beberapa faktor, di antaranya, yaitu faktor geografi di mana Indonesia terdiri dari beribu-ribu pulau kecil (*small islands*), faktor sebagai negara yang sedang berkembang di mana kota dan kabupaten mengalami perkembangan yang sangat pesat (Lasut *et al.*, 2018). Perkembangan yang pesat tersebut diikuti oleh penggunaan berbagai produk untuk memenuhi kebutuhan, termasuk produk berbahan dasar plastik, dan produksi sampah plastik yang besar; tetapi, hal ini tidak dibarengi dengan pengontrolan dan pengelolaan sampah yang memadai.

Contoh kasus, berhubungan dengan masalah sampah plastik di atas, yang sedang terjadi di Kota Manado, Provinsi Sulawesi Utara. Kota ini berukuran sedang, luas wilayah 15.726 hektar, berpenduduk hampir setengah juta jiwa, berada di pinggir pantai dan membentuk *water-front* dengan Teluk Manado (disebut sebagai *water-front city*). Keberadaan perairan Teluk Manado (TM) tidak terlepas dari keberadaan Kota Manado, padahal di bagian terluar dari perairan TM terletak perairan kawasan Taman Nasional Bunaken (TNB), dengan Pulau Bunaken sebagai destinasi wisata penyelaman. Dengan demikian, keberadaan kota akan sangat berpengaruh pada kondisi lingkungan perairan laut TNB (Lasut *et al.*, 2017).

Di perairan laut sekitar Provinsi Sulawesi Utara, ditemukan tumpukan potongan plastik yang besar di perairan sekitar Teluk Manado dan wilayah perairan Taman Nasional Bunaken (BNP) oleh Green Eye Project Aquamarine Fukushima, Jepang, pada tahun 2011 (Lasut *et al.*, 2018). Kasus lain, ditemukannya potongan plastik di dalam perut ikan 'raja laut', *living fossil*, *Latimeria menadoensis* (Lasut *et al.*, 2018). Hal ini dapat memberikan dampak dan kerugian yang besar bagi masyarakat dan pemerintah.

Sampah dari daratan Kota Manado dan sekitarnya masuk ke perairan Teluk Manado; diperkirakan sebanyak 250 m^3/hari, pada tahun 2004 (Noorden *et al.*, 2013). Produksi sampah semakin meningkat (828.812 m^3/hari pada tahun 2011 menjadi 980.865 m^3/hari pada tahun 2014) dan diperkirakan sebanyak 1.037 m^3/hari pada tahun 2015 (DLH, 2017). Jumlah sampah tersebut diperkirakan bertambah di tahun 2018; namun, kapasitas pengolahan sampah di Tempat Pembuangan Akhir (TPA) hanya sebesar 984 m^3/hari (DLH, 2017). Dengan demikian, diperkirakan sejumlah besar sampah (terutama sampah plastik) akan terbuang di perairan Teluk Manado. Hal ini merupakan satu dari sekian masalah dalam pengelolaan daerah penyelaman di Pulau Bunaken, karena selain berdampak pada keindahan perairan juga dapat mempengaruhi kelangsungan hidup biota perairan laut (Lasut *et al.*, 2017).

1.3. Pengelolaan sampah laut di Sulawesi Utara

Berbagai upaya telah dilakukan sebagai upaya pengendalian pencemaran lingkungan pesisir di perairan Teluk Manado dan melindungi ekosistem perairan TNB, di antaranya, yaitu penanganan bersama atas sampah di kawasan perairan laut TNB yang dilakukan oleh Dirjen Konservasi SDA dan Ekosistem dengan Pemerintah Provinsi Sulawesi (kerjasama telah dituangkan dalam Nota Kesepahaman No. PKS.1/KSDAE/SET/KUM.3/1/2018 dan No. 180/3/01/I/NK/2018, tanggal 11 Januari 2018). Hal ini pula sejalan dengan upaya perlindungan perairan laut wilayah Segitiga Karang (*coral triangle area*) dari pencemaran sampah plastik laut (*marine plastic debris*) yang telah dicanangkan oleh Coral Triangle Initiative (CTI). Semua upaya ini sangat relevan dengan Rencana Aksi Indonesia, "the Indonesia's Plan of Action on Marine Plastic Debris 2017-2025", di mana berupaya untuk menurunkan jumlah sampah plastik laut (*marine plastic debris*) sebanyak 70% pada tahun 2025. Sebagai bagian dari upaya tersebut di atas, maka penelitian ini diusulkan untuk dilaksanakan.

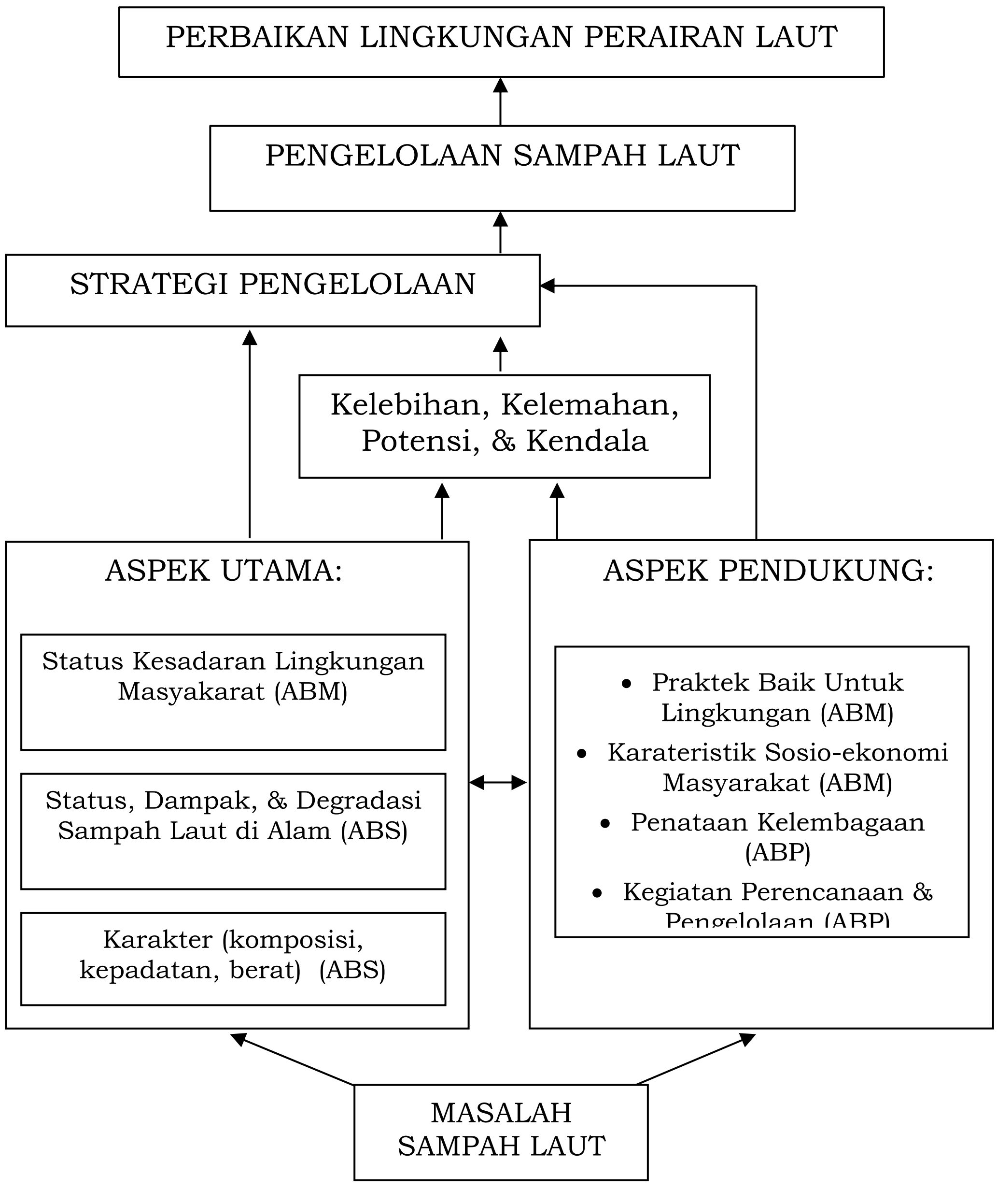
Liu *et al.* (2013) mengatakan, bahwa keberadaan sampah laut sangat erat kaitannya dengan kebijakan pengelolaan persampahan di darat. Di Kota Manado, pengelolaan sampah telah didesentralisasi ke tingkat kecamatan. Dengan kata lain, pengelolaan persampahan dilakukan masing-masing oleh kecamatan yang ada. Kebijakan ini didasari oleh Peraturan Walikota Kota Manado, Nomor 33, Tahun 2018, tentang Pengurangan dan Penanganan Sampah Berbasis Kecamatan Kota Manado.

1.4. Urgensi (Keutamaan) Penelitian

Penelitian ini sangat relevan dengan isu pencemaran sampah plastik di laut (*marine debris*) secara global. Upaya pemecahan masalah menjadi sangat penting/mendesak (*important*/*urgent*) untuk dilakukan sehingga Perserikatan Bangsa-Bangsa (PBB) menetapkan Hari Lingkungan Hidup Dunia 2018 bertemakan "Pencemaran Plastik" (*plastic pollution*). Penelitian ini juga merupakan bagian dari upaya yang sedang dilakukan dalam mencarikan pemecahan masalah yang sama di perairan laut segitiga karang (*coral triangle/CT area*), khususnya di daerah jantung (*heart*) dari perairan laut CT, yaitu Provinsi Sulawesi Utara. Upaya ini sangat relevan dengan Rencana Aksi Indonesia, "*the Indonesia's Plan of Action on Marine Plastic Debris 2017-2025*", di mana Indonesia berupaya menurunkan sampah plastik laut (*marine plastic debris*) sebanyak 70% pada tahun 2025.

1.5. Peta jalan penelitian

Gambar 1.1 menggambarkan hubungan Peta Jalan Penelitian ini. Garis besar Peta Jalan Penelitian ini terdiri dari 3 aspek yang



Gambar 1.1. Peta Jalan (*road-map*) Penelitian

berhubungan dengan masalah sampah laut, yaitu: (1) aspek yang berhubungan dengan sampah plastik (ABS); (2) aspek yang berhubungan dengan masyarakat (ABM); dan (3) aspek yang berhubungan dengan pemerintah/administratif (ABP). Penelitian yang diusulkan ini merupakan Aspek Utama Penting dari serangkaian kajian di mana merupakan akhir/puncak dari penelitian yang diusulkan (2019-2021). Dikatakan Aspek Utama Penting, karena penelitian ini akan menghasilkan luaran utama (*goal*) dari penelitian, yaitu formulasi strategi pengelolaan sampah laut Teluk Manado. Formulasi strategi pengelolaan yang dihasilkan ini merupakan dasar akademis bagi rencana pengelolaan sampah laut di Kota Manado. Dengan demikian, luaran ini akan menjadi produk UNSRAT yang direkomendasi bagi pemerintah Kota Manado.

2

Kuantifikasi Komposisi, Kepadatan, Dan Berat Sampah Laut (*Marine Litter*) Di Teluk Manado, Sulawesi Utara

DAFTAR ISI

2.1. Tujuan Penelitian

Tujuan dari penelitian ini adalah untuk:

1. Menentukan komposisi dan kepadatan sampah laut secara kuantitatif; dan
2. Menilai berat sampah laut di Perairan Teluk Manado.

2.2. Manfaat Penelitian

Penelitian ini sangat relevan dengan isu pencemaran sampah plastik di laut (*marine debris*) secara global. Upaya pemecahan masalah menjadi sangat penting/mendesak (*important*/*urgent*) untuk dilakukan sehingga Perserikatan Bangsa-Bangsa (PBB) menetapkan Hari Lingkungan Hidup Dunia 2018 bertemakan "Pencemaran Plastik" (*plastic pollution*). Penelitian ini juga merupakan bagian dari upaya yang sedang dilakukan dalam mencarikan pemecahan masalah yang sama di perairan laut segitiga karang (*coral triangle area*), khususnya di daerah jantung (*heart*) dari perairan laut CT, yaitu Provinsi Sulawesi Utara. Semua upaya ini sangat relevan dengan Rencana Aksi Indonesia, "*the Indonesia's Plan of Action on Marine Plastic Debris 2017-2025*", di mana Indonesia berupaya untuk menurunkan sampah plastik laut (*marine plastic debris*) sebanyak 70% pada tahun 2025.

2.3. Objek dan Parameter Penelitian

Penelitian ini menggunakan panduan dari Cheshire *et al*. (2009), Lippiatt *et al.* (2013), dan Anonimus (2017) dalam mengkuantifikasi sampah laut. Pengamatan terhadap sampah laut, sebagai objek penelitian, meliputi yang berukuran meso (5 mm-2,5 cm) dan makro (> 2,5 cm); yang terdampar di hamparan pantai. Untuk itu, pengamatan dilakukan menggunakan "teknik garis pantai" (*shoreline technique*) (Lippiatt *et al.*, 2013; Anonimus, 2017), yaitu sampah laut yang diamati berada di garis pantai yang terdedah pada saat pasang-surut terendah.

Untuk mencapai tujuan penelitian, parameter yang diamati ialah komposisi, kepadatan, dan berat. Parameter ini yang sementara digunakan dalam kegiatan pemantauan sampah laut di Indonesia (Anonimus, 2017); hal ini maksudkan supaya hasil penelitian ini dapat dikomparasikan dengan hasil penelitian yang sama yang dilakukan di tempat lain sehingga menjadi satu data seri.

2.4. Lokasi dan Kondisi Daerah Sampling

Pemilihan lokasi sampling sampah laut mengikuti panduan Anonimus (2017) di mana lokasi yang dipilih memenuhi kriteria sebagai berikut:

- Dapat diakses sepanjang tahun atau musiman (untuk kesinambungan pemantauan);
- Berpasir atau berkerikil;
- Tidak terdapat pemecah ombak, *jetties*, dermaga atau bangunan-bangunan lainnya;
- Kemiringan landai-moderat;
- Tidak ada aktivitas *clean up* ('bersih-bersih pantai') pada saat yang berdekatan dengan waktu sampling;
- Tidak ada pengelolaan sampah di lokasi tersebut;
- Bukan merupakan habitat sensitif, atau tidak terdapat spesies yang terancam yang mungkin terganggu akibat sampling ini; informasi ini dapat ditanyakan kepada pihak yg berkompeten dalam bidang konservasi.

Untuk memantau sampah pantai di Perairan Teluk Manado, 2 (dua) lokasi sampling dipilih, yaitu Pantai Molas dan Pantai Malalayang, yang masing-masing terletak di sebelah Utara dan Selatan Kota Manado. Kedua lokasi tersebut dianggap (berdasarkan survei awal) telah memenuhi kriteria pemilihan lokasi di atas; dengan deskripsi sebagai berikut:

2.4.1. Pantai Molas

Pantai Molas terletak di daerah sebelah Utara Kota Manado. Daerah ini dianggap mewakili daerah urban, karena berada di daerah dekat dengan kawasan perkotaan. Pantai ini berada di pinggiran muara Sungai Bailang, pada bagian selatan dan berjarak ± 1 km dari jalan raya. Pantai ini bukan merupakan pantai wisata, sehingga peruntukannya hanya bagi nelayan untuk memancing dan akses untuk menuju ke laut. Keberadaan sampah di daerah ini, umumnya berasal dari S. Bailang dan daerah laut, yang terdampar.

2.4.2. Pantai Malalayang

Pantai Malalayang terletak di daerah sebelah Selatan Kota Manado. Karena daerah ini cukup jauh berada dari pusat kota, maka dianggap sebagai daerah mewakili daerah sub-urban. Pantai ini berjarak ± 1 km dari jalan raya. Pantai ini bukan merupakan pantai wisata, sehingga peruntukannya bagi nelayan untuk memancing dan akses untuk menuju ke laut. Sumber sampah pada umumnya dari laut, yang terdampar oleh karena arus dan gelombang.

2.5. Alat dan Bahan Penelitian

Tabel 2.1 dan 2.2, menampilkan peralatan dan bahan yang digunakan dalam kegiatan pengumpulan data, baik pada saat sampling di lapangan maupun pengukuran sampel dan analisis data.

Tabel 2.1
Peralatan yang digunakan dalam kegiatan pemantauan sampah pantai di Perairan Teluk Manado, Kota Manado, Provinsi Sulawesi Utara

NAMA ALAT	KEGUNAAN
• Klinometer	Mengukur kemiringan lahan
• Timbangan (ketelitian *mg*)	Menimbang berat sampah berukuran; satuan *mg*
• Timbangan (ketelitian *g*)	Menimbang berat sampah; satuan *g*
• Kamera	Membuat gambar/video
• Kalkulator	Mengihitung
• GPS	Menentukan koordinat lokasi/titik
• Kaca pembesar/loop	Membantu visualisasi objek kecil
• Meteran gulung	Menentukan jarak
• Serokan	Mengambil sampel dalam wadah pasir/tanah
• Saringan/ayakan: ukuran ϕ 0,5 cm; ukuran bingkai 0,5 m	Menyaring sampel
• Saringan/ayakan: ukuran ϕ 2,5 cm; ukuran bingkai 0,5 m	Menyaring sampel
• Kuadran; ukuran 5 x 5 m	Batasi areal sampling
• Kuadrab; ukuran 1 x 1 m	Batas areal sampling
• Gunting, Cutter/Pisau lipat	Menggunting, Memotong
• Alat tulis menulis (pensil, clip board, spidol permanen)	Menulis, pemberian label

2.6. Metode Sampling

Sampling dilakukan menggunakan panduan Anonimus (2017), yang merupakan panduan kuatifikasi sampah laut yang dikeluarkan oleh Kementerian Lingkungan Hidup dan Kehutanan (KLHK) RI dan telah digunakan secara nasional di Indonesia. Metode ini diadaptasi untuk kondisi perairan Indonesia dari metode yang dikeluarkan oleh NOAA (Lippiatt *et al.*, 2013). Penggunaan metode di atas dalam penelitian ini dimaksudkan supaya hasil yang diperoleh dalam penelitian ini dapat dikomparasikan dengan hasil dari daerah lainnya di Indonesia sehingga menjadi satu data seri yang dapat dijadikan sebagai dasar pemantauan.

Berikut ini, tahapan dalam kegiatan sampling:

- Lokasi survei yang disampling ditentukan sepanjang 100 m, yang sejajar dengan garis pantai. Garis pertama ditetapkan pada bagian terdekat air. Keliling daerah sampling ditandai dengan menggunakan tali rafia;
- Daerah sampling, yang berjarak 100 m tersebut, di bagi menjadi 5 lajur (tegak lurus dengan garis pantai), masing-masing berjarak 20 m. Pada setiap titik daerah sampling dan lajur ditempatkan tongkat berbendera sebagai penanda;
- Dalam setiap lajur 20 m, ditentukan 2 bagian (sebagai ulangan) berukuran masing-masing 5 x 5 m, dengan menggunakan kuadran (satu bagian ke arah laut [dekat dengan air], dan satu bagian kearah darat). Bagian ini disebut Kuadran 5 x 5 m;
- Setiap bagian yang berukuran 5 x 5 m, dibuat sub-bagian berukuran 1 x 1 m sebanyak 25 bagian, dengan menggunakan kuadran. Bagian ini disebut Sub-Kuadran 1 x 1 m;
- Lima Sub-kuadran (ukuran 1 x 1 m) ditentukan secara acak yang dilakukan dengan cara pengundian;
- Di dalam setiap Sub-Kuadran 1 x 1 yang telah dipilih (5 buah), dibagi 4 bagian secara merata, yang masing-masing berukuran 0,5 x 0, 5 cm. Keempat bagian tersebut dinamai bagian A, B, C, D). Bagian A ditentukan pada sisi kira atas pada saat menghadap ke arah laut dan bagian selanjutnya (B, C, dan D) ditentukan searah dengan jarum jam;
- Sampling sampah dilakukan pada kelima Sub-Kuadran 1 x 1 m (yang telah dibagi menjadi Bagian A, B, C, D), dengan cara sebagai berikut:
  - Di Bagian A, permukaan pasir dikupas sampai pada kedalaman 5-10 cm, dan dikumpulkan (beserta dengan sampah yang ada di dalamnya) menggunakan serokan. PERHATIAN: pasir yang terkumpul tidak boleh tercampur dengan pasir pada bagian lainnya.

Tabel 2.2
Bahan yang digunakan dalam kegiatan pemantauan sampah pantai di Perairan Teluk Manado, Kota Manado, Provinsi Sulawesi Utara

NAMA BAHAN	JENIS BAHAN	KEGUNAAN
• Sarung tangan	Karet	Melindungi tangan
• Masker	Kasa	Melindungi hidung dan mulut
• Karung; ukuran 50-100 kg	Plastik	Mengumpulkan sampah
• Terpal	Plastik	
• Tongkat pembatas; ukuran 1,5 m	Kayu/ Bambu	Patok pembatas
• Bendera; bentuk segitiga; ukuran ½(30 x 30)cm	Kain	Bersama dengan patok pembatas
• Tali rafia	Plastik	Penanda batas
• Kantong bening; ukuran 3-5 kg	Plastik	Wadah sampel; 50 lembar untuk ukuran makro dan 50 lembar untuk ukuran meso.

- Saring pasir Bagian A yang telah dikumpulkan menggunakan 2 lapis saringan secara bersamaan. Saringan berukuran 0,5 cm pada bagian bawah dan Saringan berukuran 2,5 cm pada bagian atas.
- Semua sampah yang telah terkumpul pada Saringan berukuran 0,5 cm dimasukkan ke dalam wadah plastik, lalu ditutup rapat-rapat dan diberi label (nama) menggunakan Spidol Permanen.
- Di Bagian B, C, dan D, permukaan pasir dikupas sampai pada kedalaman 5-10 cm, dan dikumpulkan (beserta dengan sampah yang ada di dalamnya) menggunakan serokan. Kemudian, semua pasir yang terkumpul disaring menggunakan saringan berukuran 2,5 cm.
- Semua sampah yang telah terkumpul pada Saringan berukuran 2,5 cm ini dimasukkan ke dalam wadah plastic yang sama dengan sampah yang dikumpulkan sebelumnya di Bagian A, yang menggunakan Saringan berukuran 2,5 cm. Kemudian, ditutup rapat-rapat dan dan diberi label (nama) menggunakan Spidol Permanen.
- Semua wadah sampel yang telah terisi disimpan dengan baik untuk selanjutnya dilakukan pengklasifikasian (penggolongan) dan perhitungan Jumlah & Berat Sampah.

- Pengklasifikasian dilakukan pada semua sampah yang telah terkumpul; dilakukan satu per satu. Pengklasifikasian dilakukan dengan cara memilah;
- Sampah dipilah berdasarkan jenisnya (per jenis) dan dimasukan ke dalam wadah plastik lain yang telah disediakan. Pemilahan dilakukan dengan menggunakan panduan Anonimus (2017);
- Sampah ditimbang (berat) dan dihitung (jumlah) berdasarkan jenisnya dan data (berat dan jumlah) sampah per jenis di catat ke dalam table yang telah disediakan.

2.7. Metode Analisis Data

Data dianalisis menggunakan panduan Anonimus (2017) untuk menghitung Komposisi dan Kepadatan Sampah. Perhitungan tersebut sebagai berikut:

a. Komposisi sampah dihitung persentase (%) berat sampah per jenis per keseluruhan sampah dalam area survei:

$$\text{Komposisi (\%)} = \frac{x}{\Sigma\ x1} \times 100$$

b. Kepadatan sampah dihitung dari jumlah sampah per jenis per m^2:

$$\text{Kepadatan} = \frac{\text{jenis}}{\text{Panjang x lebar (meter)}}$$

Perhitungan dibedakan untuk sampah ukuran meso (0,5 – 2,5 cm) dan makro (> 2,5 cm).

2.8. Hasil Penelitian: Komposisi dan Kepadatan Sampah Pantai

Tabel 2.3 menampilkan hasil analisis data, khususnya Komposisi (%) dan Kepadatan (jumlah/m^2) sampah pantai berdasarkan jenis dan ukuran di Pantai Molas (daerah urban), Kota Manado, Provinsi Sulawesi Utara.

Di Pantai Molas, sampah laut berukuran Meso (0,5 – 2,5 cm) dan Makro (>2,5 cm) ditemukan dalam 41 jenis sampah di lokasi survei. Berbagai jenis sampah ditemukan, mulai dari sampah pakaian dan sepatu (CL01) dan ikat pinggang (CL02) sampai dengan sampah kayu (WD08). Jumlah tersebut mengindikasikan, bahwa beberapa jenis sampah pantai berada dalam 2 ukuran, Meso dan Makro; namun, beberapa di antaranya berada hanya dalam 1 ukuran, apakah Meso atau Makro. Dibandingkan dengan tahun 2017, di lokasi ini ditemukan 38 jenis sampah, yang terdiri dari 20 jenis berukuran Meso dan 31 jenis berukuran Makro (PPKPL-KLHK, 2017).

Komposisi (%) jenis sampah pantai terbanyak berukuran Meso, yaitu sampah plastik lainnya (PL24) sebanyak 26,91% dan sampah pecahan kaca dan keramik (GC07) sebanyak 25,19%. Sedangkan yang berukuran Makro, yaitu sampah pakaian/sepatu (CL01) sebanyak 16,20% dan kantong plastik (PL07) sebanyak 11,62% (Tabel 2.3). Komposisi sampah terbanyak pada pengamatan saat ini berbeda dengan tahun lalu (2017); pada tahun 2017, komposis terbanyak pada sampah

Tabel 2.3
Komposisi (%) dan Kepadatan (Jumlah/m²) sampah pantai berdasarkan jenis dan ukuran (Meso: 0,5 – 2,5 cm; Makro: >2,5 cm) di Pantai Molas (daerah urban), Kota Manado, Provinsi Sulawesi Utara

No	Kode	Jenis	Komposisi (%)		Kepadatan (Jumlah/m²)	
			Meso	Makro	Meso	Makro
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*
1	CL01	Pakaian, Sepatu	-	16.20	-	0.26
2	CL02	Ikat pinggang	-	0.06	-	0.02
3	CL04	Tali	0.01	0.00	0.02	0.04
4	CL06	Kain lainnya	0.04	5.06	0.02	0.32
5	FP01	Busa spons	0.10	0.30	0.02	0.02
6	FP04	Styrofoam	-	0.00	-	0.02
7	GC01	Material bangunan	8.10	1.31	0.66	0.14
8	GC02	Botol kaca	-	0.67	-	0.08
9	GC07	Pecahan kaca dan keramik	25.19	6.06	2.97	1.36
10	ME02	Tutup botol logam	-	0.03	-	0.04
11	ME03	Kaleng aluminium	-	1.53	-	0.18
12	ME04	Kaleng lainnya	-	0.11	-	0.02
13	ME08	Serpihan logam	12.00	0.70	0.81	0.14
14	ME09	Kawat	0.10	-	0.04	-
15	ME10	Peralatan bekas, paku besi	0.36	8.28	0.06	0.36
16	OT02	Alat kebersihan, pembalut dan cotton bud	-	7.60	-	0.38
17	OT03	Peralatan elektronik	-	8.84	-	0.20

(1)	(2)	(3)	(4)	(5)	(6)	(7)
18	OT04	Baterai	1.38	-	0.02	-
19	OT05	Bahan lainnya	0.08	0.68	-	0.06
20	PC05	Kertas lainnya	-	0.08	-	0.02
21	PL01	Tutup botol plastik	-	0.07	-	0.08
22	PL02	Botol plastik < 2L	-	2.41	-	0.56
23	PL03	Peralatan makanan kertas	-	0.20	-	0.06
24	PL04	Sedotan, garpu dan sendok plastik	0.37	0.06	0.10	0.10
25	PL05	Paket peralatan makanan dan minuman	2.37	3.50	0.86	2.28
26	PL06	Wadah makanan	12.90	0.80	5.36	0.24
27	PL07	Kantong plastik	7.50	11.62	1.04	2.94
28	PL08	Permainan dan perlengkapan pesta	0.14	0.93	0.04	0.30
29	PL10	Korek	-	0.16	-	0.04
30	PL11	Puntung dan filter rokok	0.01	-	0.00	-
31	PL16	Terpal, karung	-	0.59	-	0.04
32	PL18	Senar monofilament	0.02	0.05	0.00	0.04
33	PL21	Tali pita plastik	0.29	-	0.14	-
34	PL22	Serpihan fiberglass	0.19	3.19	0.03	0.18
35	PL23	Bijih plastik	1.02	-	0.26	-
36	PL24	Bahan plastik lainnya	26.91	11.21	5.47	4.26
37	RB02	Sendal dan sepatu	-	6.80	-	0.16
38	RB04	Karet ban	-	0.90	-	0.06
39	RB06	Karet gelang	0.46	-	0.10	-
40	RB08	Karet lainnya	0.15	-	0.06	-
41	WD08	Kayu lainnya	0.31	-	0.02	-

jaring ikan (PL20) sebanyak 22,6% untuk sampah yang berukuran Meso dan sampah pecahan botol (GC02) sebanyak 16,8% untuk sampah berkuran Makro (PPKPL-KLHK, 2017).

Kepadatan (jumlah/m^2) jenis sampah berukuran Meso terbanyak, yaitu sampah plastik lainnya (PL24) sebanyak 5,47 buah/m^2 dan wadah makanan (PL06) sebanyak 5,36% (Tabel 2.3). Hal ini dapat diartikan, bahwa dalam luasan 100 m^2 di pantai tersebut terdapat sebanyak 547 buah sampah plastik. Dibandingkan dengan tahun 2017, Kepadatan sampah yang ada saat ini sama di mana didominasi oleh jenis sampah plastik yang berukuran Meso (PPKPL-KLHK, 2017).

Tabel 2.4 menampilkan hasil analisis data, khususnya komposisi (%) dan kepadatan (jumlah/m^2) sampah pantai berdasarkan jenis dan ukuran di Pantai Malalayang (daerah sub-urban), Kota Manado, Provinsi Sulawesi Utara. Di Pantai Malalayang, ditemukan 30 jenis sampah di lokasi survei, yang meliputi berbagai jenis, mulai dari sampah kain (CL06) dan busa spons (FP01) sampai dengan sampah karet (RB08) dan kayu (WD06); sama halnya dengan lokasi survei di Pantai Molas. Dari 30 jenis tersebut, kedua jenis sampah ukuran Meso (0,5 – 2,5 cm) dan Makro (>2,5 cm) ditemukan. Kharakteristik sampah pantai di daerah ini berbeda dengan yang ada di Pantai Molas. Jumlah jenis sampah pada saat ini lebih banyak dari tahun 2017, yaitu sebanyak 27 jenis; demikian pula halnya jenis sampah yang mendominasi, baik yang berukuran Meso maupun berukuran Makro (PPKPL-KLHK, 2017).

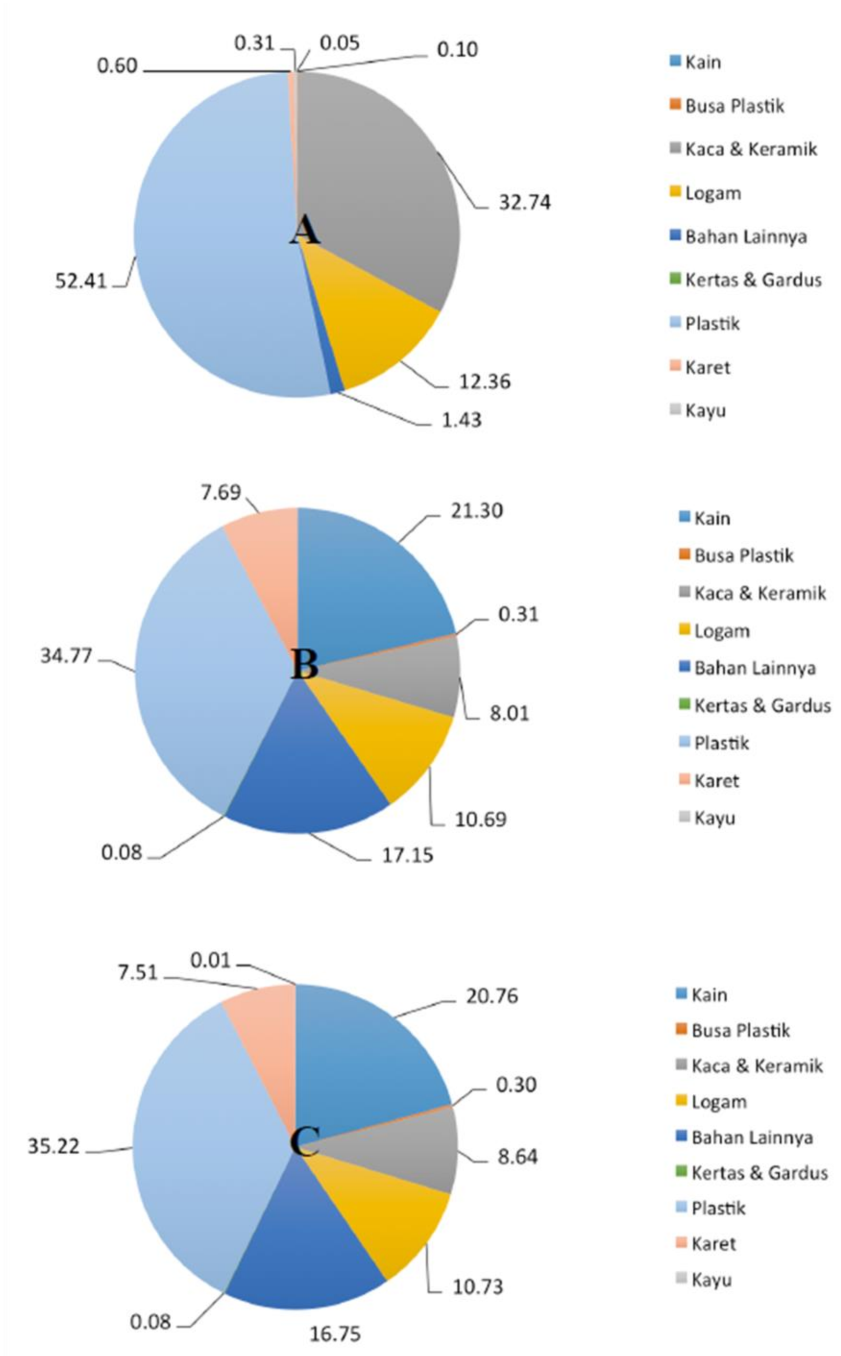
Komposisi (%) jenis sampah terbanyak berukuran Meso, yaitu sampah pecahan kaca dan keramik (GC07) sebesar 84,27%; demikian pula halnya sampah berukuran Makro (69,71%) (Tabel 2.4). Hal tersebut diikuti pula oleh Kepadatan sampah di mana sampah pecahan kaca dan keramik (GC07), baik untuk ukuran Meso (4,30 buah/m^2) maupun ukuran Makro (2,90 buah/m^2) (Tabel 2.4).

Tabel 2.4
Komposisi (%) dan Kepadatan (Jumlah/m^2) sampah pantai berdasarkan jenis di Pantai Malalayang (daerah sub-urban), Kota Manado, Provinsi Sulawesi Utara

No	Kode	Jenis	Komposisi (%)		Kepadatan (Jumlah/m^2)	
			Meso	Makro	Meso	Makro
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*
1	CL06	Kain lainnya	-	0.07	-	0.04
2	FP01	Busa spons	0.01	-	0.02	-
3	FP04	Styrofoam	0.05	1.61	0.10	0.32
4	GC01	Material bangunan	0.43	2.44	0.04	0.20
5	GC03	Peralatan makan	-	0.22	-	0.04
6	GC07	Pecahan kaca dan keramik	84.27	69.71	4.30	2.90
7	ME02	Tutup botol logam	-	0.33	-	0.08
8	ME04	Kaleng lainnya	0.04	-	0.02	-
9	ME08	Serpihan logam	1.73	1.14	-	0.08
10	ME10	Logam lainnya	0.68	1.10	0.10	0.18

(1)	(2)	(3)	(4)	(5)	(6)	(7)
11	OT03	Peralatan elektronik	0.37	0.05	0.06	0.08
12	PC03	Bungkus rokok, bungkus makanan	0.08	0.04	0.06	0.04
13	PL01	Tutup botol plastik	-	0.16	-	0.12
14	PL02	Botol Plastik	-	10.97	-	0.56
15	PL03	Plastik jerigen	0.34	-	0.02	-
16	PL04	Sedotan	-	0.01	-	0.04
17	PL05	Paket peralatan minuman dan makanan	-	3.42	-	0.84
18	PL06	Plastik wadah makanan	-	0.20	-	0.16
19	PL07	Kantong plastik	-	0.24	-	0.08
20	PL11	Puntung rokok	0.01	0.00	0.02	0.04
21	PL17	Peralatan memancing	0.04	-	0.02	-
22	PL18	Senar monofilament	0.02	0.01	0.02	0.04
23	PL21	Tali pita plastik	-	5.18	-	0.12
24	PL22	Serpihan fiberglass	0.14	4.86	0.02	0.24
25	PL24	Bahan plastik lainnya	11.31	0.02	1.24	0.04
26	RB02	Sendal	0.27	-	0.04	-
27	RB04	Karet ban	-	0.26	-	0.12
28	RB05	Ban dalam	-	0.01	-	0.04
29	RB08	Karet lainnya	0.21	0.13	0.02	0.08
30	WD06	Kayu lainnya	-	0.04	-	0.04

Komposisi sampah laut di Pantai Molas, berdasarkan jenis bahan, ditampilkan pada Gambar 2.1; baik berukuran Meso (Gambar 2.1.A) maupun berukuran Makro (Gambar 2.1.B). Untuk ukuran Meso, nampak, ditemukan 8 jenis bahan sampah laut, yaitu kain, busa plastik, kaca & keramik, logam, plastik, karet, kayu, dan bahan lainnya. Komposisi sampah tertinggi berasal dari jenis bahan plastik (52,41%) dan kaca & keramik (32,74%); dan terendah dari jenis bahan kain (0,05%). Untuk ukuran Makro, juga ditemukan 8 jenis bahan sampah, yaitu kain, busa plastik, kaca & keramik, logam, kertas & gardus, plastik, karet, dan bahan lainnya. Seperti halnya sampah berukuran Meso, bahan plastik memiliki komposisi tertinggi untuk sampah berukuran Makro, yaitu sebesar 34,77%. Namun, komposisi kedua tertinggi dari sampah ukuran ini berasal dari kain (21,30%). Komposisi terendah adalah sampah jenis kertas & gardus (0,08%). Secara keseluruhan, jenis bahan sampah laut yang memiliki komposisi tertinggi adalah plastik (35,22%) dan kain (20,76%) (Gambar 2.1.C).



Gambar 2.1. Komposisi (%) jenis bahan sampah laut di Pantai Molas berdasarkan bukuran Meso (A) dan Makro (B) dan keseluruhan (C).

Di Pantai Malalayang, komposisi sampah laut tertinggi yang berukuran Meso adalah berasal dari jenis bahan kaca & keramik (84,69%) dan plastik (11,86), dan yang terendah adalah berasal dari jenis bahan busa plastik (0,16%) (Gambar 2.2.A). Demikian pula halnya untuk sampah laut berukuran Makro, komposisi tertinggi berasal dari jenis bahan kaca & keramik (72,36%) dan plastik (22,86) (Gambar 2.2.B). Secara keseluruhan, jenis bahan sampah laut yng memiliki komposisi tertinggi adalah kaca & keramik (73,82%) dan plastik (21,56%) (Gambar 2.2.C).

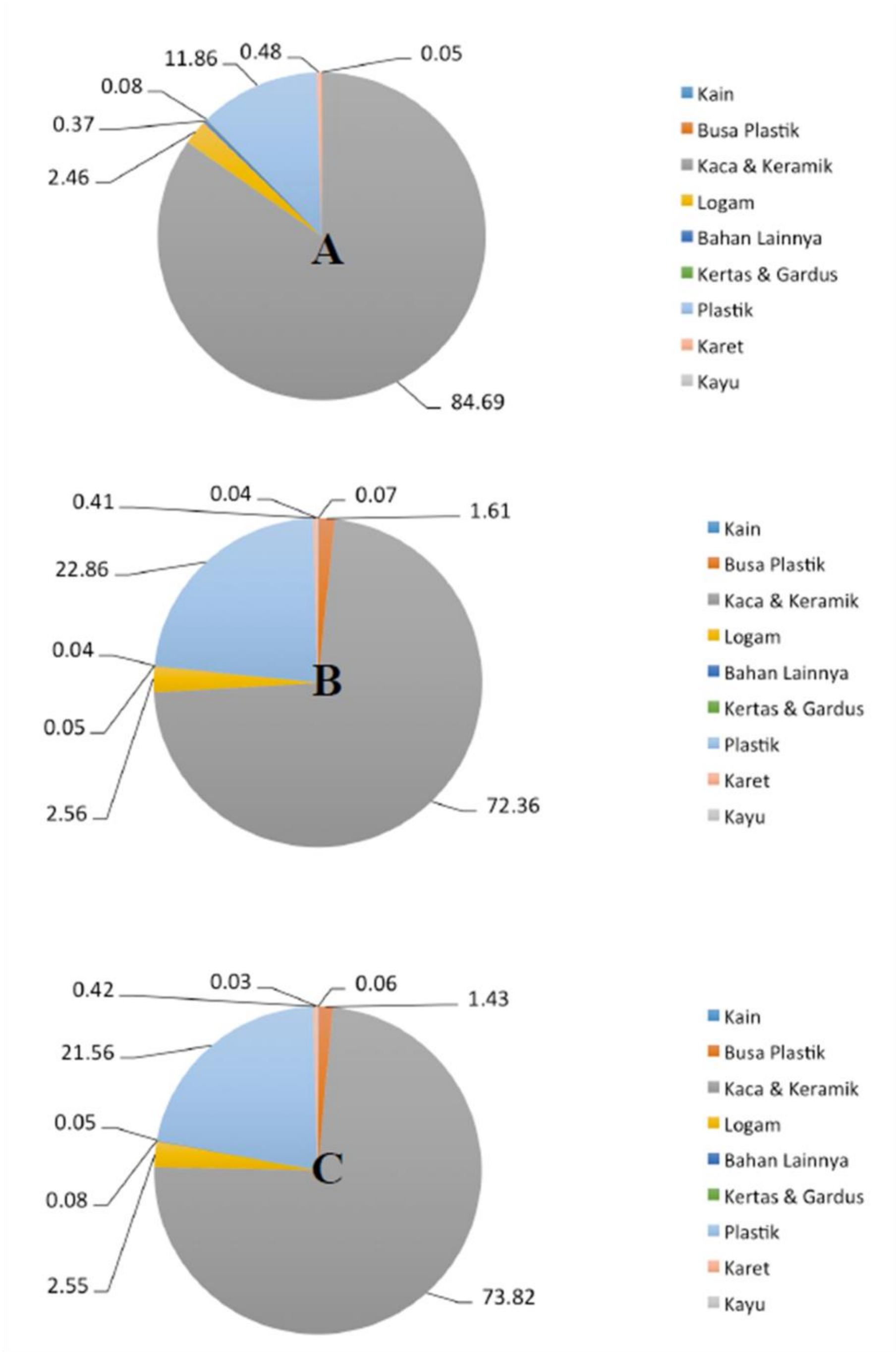
Berdasarkan pengamatan di kedua lokasi survei, Pantai Molas dan pantai Malalayang, maka dapat kuantifikasi komposisi sampah laut di Teluk Manado berdasarkan ukuran dan jenis bahan. Untuk kedua ukuran sampah laut (Meso dan Makro), 9 jenis bahan sampah laut ditemukan, yaitu bahan kain, busa plastik, kaca & keramik, logam, kertas & gardus, plastik, karet, kayu, dan bahan lainnya. Secara keseluruhan, komposisi tertinggi didominasi oleh jenis bahan plastik (33,14%), kaca & keramik (18,56%), dan kain (17,61%) (Gambar 2.3).

Komposisi sampah laut di Teluk Manado (Gambar 2.3) diringi oleh berat dan jumlah dari masing-masing jenis bahan sampah di mana secara keseluruhan berat dan jumlahnya masing-masing sebesar 17.103,67 g dan 1.142,84 buah. Sedangkan, kepadatan masing-masing jenis bahan sampah tersebut (dari tinggi ke rendah) adalah plastik (28,04 buah/m^2), kaca & keramik (12,69 buah/m^2), logam (2,11 buah/m^2), bahan lainnya (0,8 buah/m^2), kain (0,72 buah/m^2), karet (0,68 buah/m^2), busa plastik (0,50 buah/m^2), kertas & gardus (0,12 buah/m^2), dan kayu (0,06 buah/m^2).

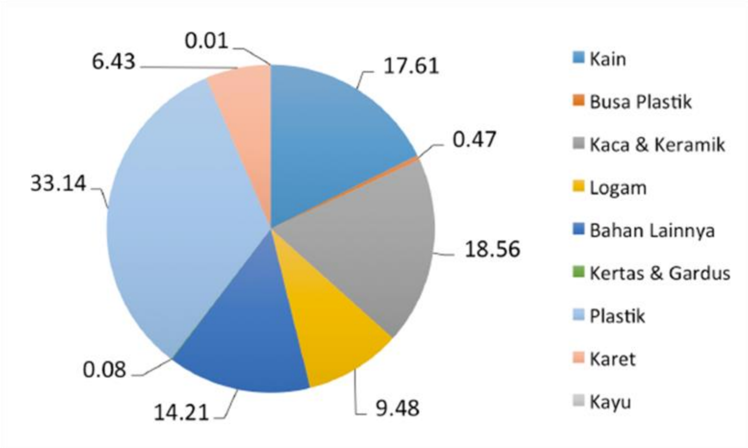
Perihal bahan plastik yang mendominasi berat, jumlah, kepadatan, dan komposisi sampah laut di Teluk Manado, Gambar 2.4 menampilkan 17 item dari bahan plastik tersebut berdasarkan berat (g).

2.9. Jumlah Sampah Pantai

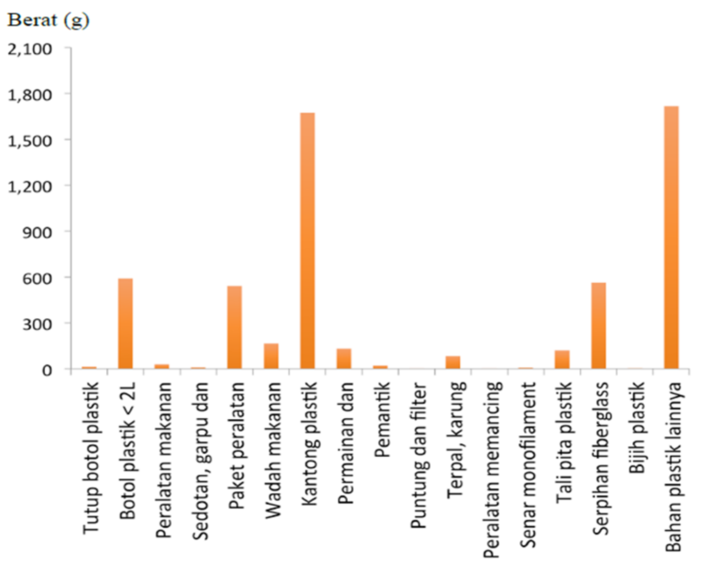
Tabel 2.5 menampilkan Berat (g) dan Jumlah (buah) sampah pantai yang ditemukan di kedua lokasi pengamatan di Kota Manado (Pantai Malalayang dan Pantai Molas), baik berukuran Makro maupun Meso. Berat keseluruhan sampah laut di Pantai Malalayang ialah sebesar 2.603,59 g; sedangkan di Pantai Molas sebesar 14.500,08 g. Total berat sampah laut di Teluk Manado adalah sebesar 17.103,67 g. Jumlah keseluruhan sampah laut di Pantai Malalayang adalah sebanyak 315,60 buah; sedangkan di Pantai Molas sebanyak 827,25 buah. Total jumlah sampah laut di Teluk Manado adalah sebanyak 1.142,84 buah.



Gambar 2.2. Komposisi (%) jenis bahan sampah laut di Pantai Malayang berdasarkan ukuran Meso (A) dan Makro (B) dan keseluruhan (C)



Gambar 2.3. Komposisi (%) sampah laut di Teluk Manado berdasarkan jenis bahan



Gambar 2.4. Berat (g) item penyusun sampah plastik di Teluk Manado

Tabel 2.5
Berat (g) dan jumlah(buah) sampah pantai di Teluk Manado berdasarkan 2 lokasi pengamatan (Pantai Malalayang dan Pantai Molas)

Parameter	Satuan	Lokasi	Ukuran Sampah		Sub-Total	TOTAL
			Makro	Messo		
Berat Sampah Pantai yang dipantau	(g)	Malalayang	2.296,21	307,38	2.603,59	17.103,67
		Molas	14.130,16	369,92	14.500,08	
Jumlah Sampah Pantai yang dipantau	(buah)	Malalayang	163,00	152,60	315,60	1.142,84
		Molas	375,00	452,25	827,25	

Dibandingkan dengan tahun 2017 di mana berat sampah laut yang ditemukan sebesar 1.658,74 g, maka berat sampah laut di Teluk Manado pada tahun 2019 ini (17.103,67 g) naik sebesar lebih 10 kali.

2.10. Kesimpulan

1. Komposisi sampah laut di Teluk Manado, Kota Manado, terdiri dari 9 jenis bahan, yaitu plastik, kaca & keramik, kain, logam, karet, busa plastik, kertas & gardus, kayu, dan bahan lainnya. Kepadatan sampah laut di Teluk Manado, berdasarkan jenis bahan adalah plastik, kaca & keramik, logam, bahan lainnya, kain, karet, busa plastik, kertas & gardus, dan kayu.
2. Berat sampah laut di Teluk Manado, Kota Manado, adalah sebesar 17.103,67 g.

3

Status, Dampak, Kesadaran Lingkungan Masyarakat, Dan Penataan Kelembagaan Sistem Pengelolaan Sampah Laut Teluk Manado

DAFTAR ISI

3.1. Tujuan Penelitian

Kegiatan penelitian yang direncanakan ini merupakan bagian dari serangkaian penelitian, yang secara umum, bertujuan untuk menyusun/merancang suatu strategi dan model pengelolaan sampah laut (marine litter) untuk kota pesisir Manado, Provinsi Sulawesi Utara. Adapun tujuan khusus dari penelitian ini ialah untuk:

3. Mengevaluasi status pengelolaan sampah di darat Kota Manado;
4. Mendeskripsikan dampak dan degradasi sampah laut di alam;
5. Mengidentifikasi dan menganalisis kesadaran lingkungan masyarakat yang berhubungan dengan pembuangan sampah;
6. Mengevaluasi penataan kelembagaan yang berhubungan dengan sistem pengelolaan persampahan; dan
7. Mengidentifikasi, menganalisis, dan mengevaluasi kegiatan perencanaan dan pengelolaan sampah di Kota Manado.

3.2. Manfaat Penelitian

Penelitian ini memberi manfaat untuk hal-hal sebagai berikut:

- Peningkatan peran serta UNSRAT dalam membantu memecahkan masalah lingkungan di Kota Manado, khususnya dalam program pembangunan berkelanjutan;
- Memberikan jawaban bagaimana cara memecahkan masalah sampah laut di Kota Manado, Provinsi Sulawesi Utara, sebagai upaya perbaikan kualitas lingkungan perairan Taman Nasional Bunaken.

3.3. Kerangka Kerja Penelitian

Untuk mencapai tujuan utama dari penelitian ini (yaitu: perbaikan lingkungan perairan laut melalui, yang diawali dengan perencanaan pengelolaan sampah laut yang komprehensif dan holistik), maka beberapa aspek yang dikaji dalam penelitian ini, yaitu:

<u>Kajian 1: Status pengelolaan sampah di darat.</u> Aspek ini dikaji untuk mengevaluasi secara kualitatif sistem pengelolaan sampah di sepanjang sungai yang masuk ke Teluk Manado (Tujuan 1). Variabel yang diamati, yaitu:

- *Sumber spesifik (point sources)*, yaitu permukiman, perkantoran, kegiatan bisnis.
- *Sumber tidak spesifik (non-point sources)*, yaitu sumber dari tempat umum.
- *Sistem pengelolaan persampahan*, yaitu fasilitas tempat sampah, tempat pembuangan sementara, tempat pembuangan akhir, dan sistem pengelolaan sampah setempat (on-site waste management).

Kajian 2: Dampak & degradasi sampah laut di alam. Dampak dan degradasi sampah laut di alam dideskripsi pada pada kajian ini (Tujuan 2). Jenis sampah laut yang dideskripsi yaitu jenis bahan sampah laut yang dikumpulkan berdasarkan penelitian yang telah dilakukan sebelumnya (Lasut dkk., 2019). Variabel yang dideskripsi, yaitu:

- *Dampak sampah laut.*
- *Jangka waktu degradasi sampah laut berdasarkan jenis bahan.*

Kajian 3: Status kesadaran lingkungan masyarakat. Aspek ini digunakan untuk mengidentifikasi dan menganalisis kesadaran lingkungan masyarakat yang berhubungan dengan pembuangan sampah (Tujuan 3). Variabel yang digunakan adalah:

- Perasaan (feeling) terhadap lingkungan. Hal yang dikaji yaitu menyangkut persepsi masyarakat terhadap masalah lingkungan yang disebabkan oleh sampah dan keinginan untuk memecahkan masalah sampah.
- Keprihatinan terhadap masalah lingkungan. Sikap terhadap isu lingkungan dan masalah yang disebabkan oleh sampah dikaji.

Kajian 4: Penataan kelembagaan. Aspek ini dikaji untuk mengevaluasi penataan kelembagaan, yang berhubungan dengan sistem pengelolaan persampahan (Tujuan 4). Variabel yang digunakan adalah:

- Pihak pemerintah lokal (Kota Manado) & regional (Provinsi Sulawesi Utara). Komponen yang diamati, yaitu struktur, peranan & fungsi, tanggung jawab, dan koordinasi;
- Pihak masyarakat. Komponen yang diamati, yaitu tipe kelembagaan, peranan & fungsi, tanggung jawab, dan koordinasi.

Kajian 5: Kegiatan perencanaan dan pengelolaan. Aspek ini dikaji dalam rangka untuk mengidentifikasi, menganalisis, dan mengevaluasi kegiatan perencanaan dan pengelolaan sampah, termasuk pula teknik-teknik yang digunakan dalam pemecahan masalah; praktek baik untuk lingkungan (best environmental practices) juga dikaji (Tujuan 5). Berikut adalah komponen dan variabel yang digunakan:

a. Untuk kegiatan perencanaan dan pengelolaan.

- Kegiatan administrasi. Komponen yang diamati adalah kebijakan yang ada, perundang-undangan, peraturan.

- Kegiatan sosial. Komponen yang diamati adalah pengembangan kapasitas yang ada, pengelolaan bersama dan berbasis masyarakat, dan pelaksanaannya.
- Kegiatan teknis: Komponen yang diamati adalah analisis dampak lingkungan yang ada, sistem pengelolaan resiko.

b. Untuk praktek baik untuk lingkungan (best environmental practices). Komponen yang diamati adalah kegiatan-kegiatan yang telah dilakukan, baik oleh pemerintah maupun masyarakat, dan potensi yang dapat dilakukan/dikembangkan.

3.4. Rancangan Penelitian

Kegiatan penelitian yang dirancang dalam usul penelitian ini mempertimbangkan bahwa penelitian ini dapat dilakukan kembali untuk dilakukan pemantauan dan evaluasi atau untuk membandingkannya dengan kasus-kasus lainnya di tempat lain. Berdasarkan aspek yang dikaji, penelitian ini dirancang sebagai berikut:

Kajian 1: Status pengelolaan sampah di darat. Aspek ini dikaji secara kualitatif. Data yang digunakan adalah data primer, yang dikumpulkan dengan menggunakan metode survei lapangan. Tiga sungai besar yang dimati, yaitu: S. Bailang, S. Tondano, dan S. Sario. Selain sungai, pengamatan juga dilakukan di beberapa lokasi yang diduga menjadi sumber bahan pencemar yang masuk ke teluk. Lokasi Pengamatan di ketiga sungai dan lokasi lainnya ditampilkan dalam Tabel 3.1 dan dipetakan dalam Gambar 3.1.

Kajian 2: dampak dan degradasi sampah laut di alam. Aspek ini dikaji dengan menggunakan data sekunder, yang bersumber dari literatur ilmiah (jurnal, laporan, dll.).

Kajian 3: Status kesadaran lingkungan masyarakat. Aspek ini dikaji secara kuantitatif. Data yang digunakan adalah data primer. Pengumpulan data dilakukan pada masyarakat yang berdomisili di dalam dan di luar Kota Manado. Jumlah sampel/responden yang dimati yaitu sebesar 161 orang. Metode sampling menggunakan *stratified random sampling.*

Kajian 4: Penataan kelembagaan. Aspek ini dikaji pada lokasi keseluruhan Kota Manado. Aspek ini dideskripsi secara kualitatif.

Kajian 5: Kegiatan perencanaan dan pengelolaan. Aspek ini dideskripsi secara kualitatif.

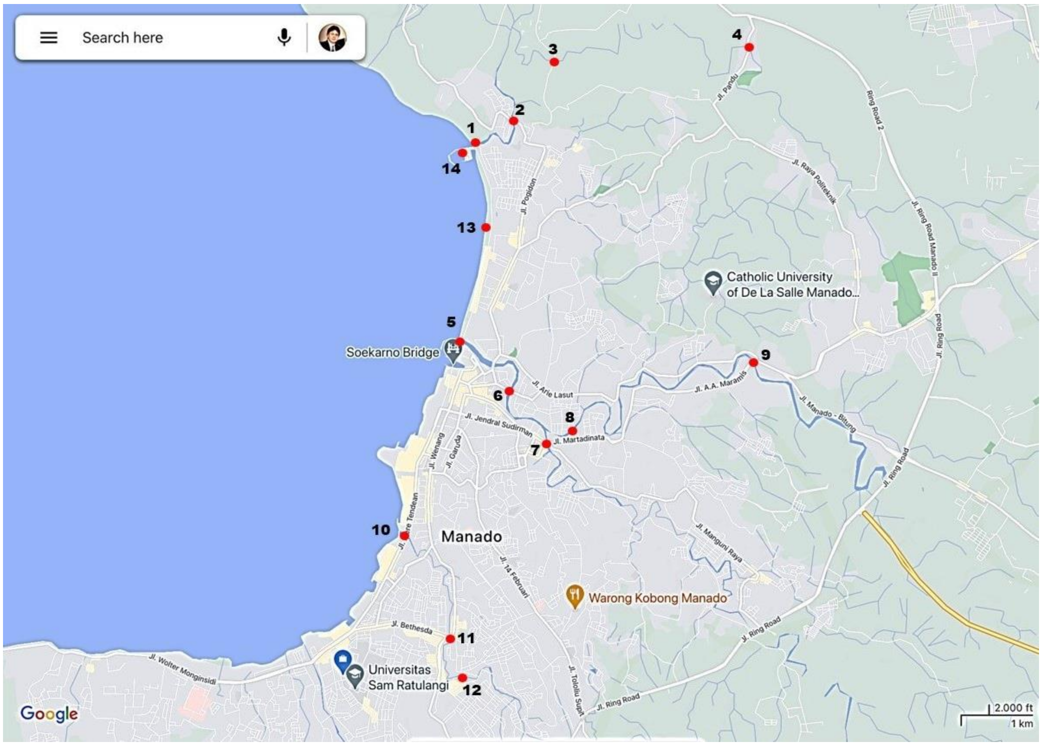
Tabel 3.1
Lokasi Pengamatan kondisi sumber pencemar yang masuk ke Teluk Manado

LOKASI PENGAMATAN	NAMA LOKASI	LU	BT	KETERANGAN
Sungai Bailang:				
1	Muara Sungai Bailang	1.524344°	124.842657°	Muara sungai
2	Jembatan Bailang	1.527187°	124.847614°	Daerah campuran permukiman dan perkebunan
3	Jembatan di Kelurahan Bailang	1.534919°	124.852694°	Daerah campuran permukiman dan perkebunan
4	Jembatan Bengkol	1.537306°	124.877220°	Daerah perkebunan
Sungai Tondano:				
5	Jembatan Soekarno	1.499587°	124.840960°	Muara sungai
6	Jembatan Mahakam	1.493101°	124.846971°	Daerah permukiman
7	Jembatan Miangas	1.486480°	124.851704°	Daerah Permukiman
8	Jembatan Ketang	1.488166°	124.854775°	Daerah Permukiman
9	Jembatan Kairagi	1.496820°	124.877782°	Daerah campuran permukiman dan perkebunan
Sungai Sario:				
10	Jembatan Kuning	1.474823°	124.833671°	Muara sungai
11	Jembatan Pakowa	1.461972°	124.839134°	Daerah permukiman
12	Jembatan Pasar Karombasan	1.457046°	124.840904°	Pasar Karombasan
Lainnya:				
13	Jembatan Maasing	1.514325°	124.844745°	Muara sungai
14	TPI Tumumpa	1.523738°	124.841165°	Tempat pendaratan dan pelelangan ikan

3.5. Prosedur Pengumpulan Data

Dua tipe data yang dikumpulkan, yaitu data primer dan sekunder. Data Primer dikumpulkan langsung dari lapangan sebagai sumber utama, dan Data Sekunder dikumpulkan dari berbagai sumber dokumen, arsip, dan lain-lain (misalnya tabel, laporan, statistik, peraturan, ahli). Prosedur pengumpulan data dilakukan seperti sebagai berikut:

- Pengumpulan Data Sekunder (DS). Data/informasi sekunder yang tersedia diperoleh dari berbagai sumber.
- Pengumpulan Data Primer (DP). Dalam penelitian ini, pengumpulan data primer (DP) dilakukan dalam 2 (dua) tahapan, yaitu:



Gambar 3.1. Lokasi Pengamatan kondisi sumber pencemar yang masuk ke Teluk Manado (1-4: di S. Bailang; 5-9: di S. Tondano; 10-12: di Sungai Sario).

Tahap 1: Survei Awal. Survei Awal dilakukan terlebih dahulu sebagai survei reconnaissance dalam rangka untuk mencoba-cocokkan rancangan penelitian yang telah dibuat (misalnya daerah studi, daerah sampling, sampling, untuk melakukan uji awal terhadap angket yang telah dibuat, dan mengurus perizinan.

Tahap 2: Survei Inti. Survei inti dilakukan setelah selesai melakukan Survei Awal.

3.6. Analisis Data

Dua macam Analisis Statistika (uji Statistika) digunakan dalam penelitian ini, yaitu parametrik (analisis kuantitatif) dan non-parameterik (analisis kualitatif). *Analysis of Variance*/ANOVA (Uji Sidik Ragam) digunakan untuk membandingkan aspek-aspek yang lebih dari satu variabel dan mempunyai data terdistribusi secara normal (Fowler & Cohen 1990). Uji-Chi-square (χ^2) and Uji-t digunakan untuk membandingkan perbedaan variabel-variabel antara 2 kelompok populasi (Steel & Torrie 1980).

3.7. Hasil Penelitian: Pengelolaan Sampah di Darat

Gambar 3.2, Gbr. 3.3, dan Gbr. 3.4 menampilkan kondisi 3 sungai yang menuju ke Teluk Manado (berturut-turut S. Bailang, S. Tondano, dan S. Sario) di beberapa titik pengamatan berdasarkan keberadaan sampah di sepanjang aliran sungai. Gambar 3.5 menampilkan tempat lainnya yang merupakan sumber sampah yang menuju ke teluk. Keberadaan sampah di sepanjang sungai sangat erat kaitannya dengan sistem pengelolaan sampah di darat. Dengan demikian, bisa dikatakan, bahwa, keberadaan sampah di sepanjang aliran sungai-sungai ini dapat menggambarkan keberadaan pengelolaan sampah di darat, khususnya di daerah sekitar sungai dan lokasi pengamatan.

Gambar 3.2. Kondisi sampah di sepanjang aliran Sungai Bailang

Gambar 3.3. Kondisi sampah di sepanjang aliran Sungai Tondano

Sungai Bailang, yang berada di bagian Utara Kota Manado, mengalirkan air dari dataran tinggi ke dataran rendah, Teluk Manado. Sungai ini melintas di beberapa daerah permukiman di daerah perdesaan (*rural*) dan daerah perkebunan dan hutan. Membandingkan ke dua daerah yang dilintasi tersebut, daerah perkebunan dan hutan merupakan daerah yang paling banyak.

Keberadaan sampah di sepanjang aliran sungai, yang diamati secara kualitatif di 4 lokasi pengamatan (Gambar 3.2), tidak banyak, kecuali di muara sungai (Lokasi Pengamatan 1). Jenis bahan sampah yang terbanyak ditemukan, yaitu jenis plastik dan kertas; dalam keadaan potongan (fragmen) kecil-kecil. Di muara sungai, jenis bahan sampah plastik juga terbanyak ditemukan, namun jenis bahan lainnya juga ditemukan, yang meliputi kertas, kaca & keramik, logam, karet, kayu, spongs. Namun demikian, sampah hayati dari perkebunan dan hutan ditemukan sangat dominan di sepanjang aliran sungai.

Gambar 3.4. Kondisi sampah di sepanjang aliran Sungai Sario

Sungai Tondano merupakan sungai terbesar yang melintasi Kota Manado, jika dibanding dengan 6 sungai lainnya. Sumber air sungai ini berasal dari dataran tinggi dan Danau Tondano; melintasi banyak permukiman dan perkebunan-hutan. Daerah permukiman yang dilalui meliputi dari daerah permukiman perdesaaan (*rural*) yang jarang penduduk sampai pada daerah permukiman perkotaan (*urban*) yang padat penduduk di Kota Manado.

Keberadaan sampah di sepanjang aliran sungai, yang diamati secara kualitatif di lokasi pengamatan (Gambar 3.3) di Kota Manado, banyak, terlebih di muara sungai (Lokasi Pengamatan 5). Diduga sungai inilah yang paling banyak mensuplai sampah dari daratan menuju ke Teluk Manado.

Banyaknya sampah di aliran sungai, diamati, disebabkan oleh buangan langsung dari daerah permukiman. Adanya tempat pembuangan sampah sementara (TPS) di pinggir sungai ini bisa menjadi penyebab. Diduga, masyarakat masih menggunakan sungai ini sebagai tempat buang sampah secara ilegal, walaupun praktek ini tidak ditemukan pada saat pengamatan dalam penelitian ini.

Sungai Sario berada di bagian Selatan Kota Manado dan melintasi daerah permukiman (*rural*) dan perkebunan. Namun, pada bagian dekat muara, daerah yang dilintasi merupakan daerah perkotaan (*urban*) yang padat penduduknya. Nampak, pada bagian-bagian tertentu, sungai ini mengalami penyempitan, yang disebabkan oleh penggunaan lahan untuk permukiman.

Keberadaan sampah di sepanjang aliran sungai, yang diamati secara kualitatif (Gambar 3.4), tidak banyak, karena umumnya melintasi daerah perkebunan. Namun, oleh karena pada satu bagian di pinggir aliran sungai ini di tempati oleh kegiatan pasar tradisional (Lokasi Pengamatan 12), nampak sampah banyak mulai dari lokasi ini. Sampah, yang bersumber dari pasar tersebut (LP 12), bertambah banyak yang bersumber dari daerah permukiman di dekat muara. Bersama dengan S. Tondano, sungai ini juga diduga memberikan kontribusi yang besar terhadap keberadaan sampah laut di Teluk Manado.

Daerah lainnya di Kota Manado, yang dianggap merupakan sumber sampah ke Teluk Manado, yaitu kegiatan TPI Tumumpa, yang berada di pinggir pantai (Lokasi Pengamatan 14). Dalam kegiatan ini, jenis bahan plastik banyak digunakan dan terbuang ke perairan (Gambar 3.5). Oleh karena itulah, maka kegiatan ini dianggap sebagai sumber sampah ke Teluk Manado.

Tabel 3.2 menampilkan ringkasan kondisi sampah di aliran sungai yang menuju ke laut di Kota Manado pada semua Lokasi Pengamatan. Tabel 3.3 menampilkan kondisi sampah di lokasi lainnya merupakan sumber sampah bagi keberadaan sampah laut di Teluk Manado.

3.8. Hasil Penelitian: Status Kesadaran Lingkungan Masyarakat

Sebanyak 161 orang responden yang terlibat dalam studi ini. Adapun kharakteristik mereka (gender, pendidikan, pekerjaan, pendapatan, dan tempat tinggal) ditampilkan pada Gambar 3.6. Keterlibatan responden dilakukan menggunakan teknik *stratified random sampling*.

Keterlibatan responden dalam studi ini dilakukan dengan cara mengisi angket yang disediakan secara daring (online). Sebelum responden diundang untuk terlibat, angket telah disiapkan menggunakan Google Form (GF) di mana berisi pertanyaan sesuai topik, yang adalah satu aplikasi yang disediakan oleh Google®. Distribusi ang-

Gambar 3.5. Situasi dan kondisi TPI Tumumpa sebagai sumber sampah ke Teluk Manado

ket dalam GF tersebut dilakukan melalui media sosial, yaitu Facebook® dan WhatsApps®. Jawaban responden terhadap angket tersebut dikumpulkan secara daring (online) dalam aplikasi GF. Analisis data dan presentasi hasil melalui diagram juga dilakukan secara online dalam aplikasi GF.

Tabel 3.4 menunjukkan hasil penelitian mengenai Tingkat Keprihatinan (TP) masyarakat (berbasis perorangan) tentang kondisi lingkungan yang berhubungan dengan sampah. Tabel 3.5 menunjukkan hasil penelitian tentang Keinginan Masyarakat (basis perorangan) tentang penyelesaian masalah lingkungan, termasuk masalah buangan sampah

3.9. Hasil Penelitian: Dampak & Degradasi Sampah Laut

Jenis bahan sampah laut yang ditemukan di perairan Teluk Manado dapat diklasifikasi ke dalam 9 jenis (Lasut *et al.*, 2019). Semua bahan tersebut berhubungan erat dengan kegiatan sehari-hari masyarakat. Kesembilan bahan tersebut, yaitu a) plastik (*plastic*), b) busa plastik (*foamed plastic*), c) kain (*cloth*), d) kaca & keramik (*glass & ceramic*), e) logam (*metal*), f) karet (*rubber*), g) kayu (*wood*), h) kertas & kardus (*paper & cardboard*), dan i) bahan lainnya (*other*). Dampak dan jangka waktu degradasi sebagian jenis bahan sampah laut tersebut dijelaskan pada Tabel 3.6.

Tabel 3.2
Kondisi sampah di aliran sungai yang menuju ke laut di Kota Manado

LOKASI PENGAMATAN	NAMA LOKASI	POSISI / KONDISI SAMPAH DI ALIRAN SUNGAI / SUMBER SAMPAH
Sungai Bailang:		
1	Muara Sungai Bailang	- Muara sungai - Banyak sampah - Sampah berada di sepanjang aliran sungai. Sumber sampah berasal dari permukiman dan berbagai tempat
2	Jembatan Bailang	- Daerah campuran permukiman dan perkebunan - Sedikit sampah - Sampah berada di sepanjang aliran sungai. Sumber sampah berasal dari permukiman dan berbagai tempat
3	Jembatan di Kelurahan Bailang	- Daerah campuran permukiman dan perkebunan - Sedikit sampah - Sumber sampah berasal dari permukiman dan berbagai tempat
4	Jembatan Bengkol	- Daerah perkebunan - Sedikit sampah - Sumber sampah berasal dari permukiman dan berbagai tempat
Sungai Tondano:		
5	Jembatan Soekarno	- Muara sungai - Banyak sampah - Sampah berada di sepanjang aliran sungai. Sumber sampah berasal dari permukiman dan berbagai tempat
6	Jembatan Mahakam	- Daerah permukiman - Banyak sampah - Sampah berada di sepanjang aliran sungai. Sumber sampah berasal dari permukiman dan berbagai tempat
7	Jembatan Miangas	- Daerah Permukiman - Banyak sampah - Sumber sampah berasal dari permukiman dan berbagai tempat

LOKASI PENGAMATAN	NAMA LOKASI	POSISI / KONDISI SAMPAH DI ALIRAN SUNGAI / SUMBER SAMPAH
8	Jembatan Ketang	- Daerah Permukiman - Banyak sampah - Sumber sampah berasal dari permukiman dan berbagai tempat
9	Jembatan Kairagi	- Daerah campuran permukiman dan perkebunan - Sedikit sampah - Sumber sampah berasal dari permukiman dan berbagai tempat
Sungai Sario:		
10	Jembatan Kuning	- Muara sungai - Banyak sampah - Sampah berada di sepanjang aliran sungai. Sumber sampah berasal dari permukiman dan berbagai tempat
11	Jembatan Pakowa	- Daerah permukiman - Banyak sampah - Sampah berada di sepanjang aliran sungai. Sumber sampah berasal dari permukiman dan berbagai tempat
12	Jembatan Pasar Karombasan	- Daerah Pasar & permukiman - Banyak sampah - Sampah berada di sepanjang aliran sungai. Sumber sampah berasal dari pasar dan permukiman serta berbagai tempat

3.10. Hasil Penelitian: Penataan Kelembagaan

Kelembagaan yang berhubungan dengan sistem pengelolaan persampahan, termasuk sampah laut di Teluk Manado, meliputi kelembagaan pemerintah, baik yang berada di tingkat Kota Manado maupun di tingkat Provinsi Sulawesi Utara, dan kelembagaan masyarakat. Informasi berikut ini merupakan penjelasan tentang kelembagaan tersebut:

a. Kelembagaan Pemerintah Kota Manado

Lembaga di Pemerintah Kota Manado yang menangani pengelolaan persampahan, termasuk pengelolaan sampah laut, adalah

Dinas Lingkungan Hidup Daerah (DLHD) Kota Manado, di bawah kewenangan walikota.

Tabel 3.3
Kondisi sampah di tempat lainnya yang menuju ke laut di Kota Manado

LOKASI PENGAMATAN	NAMA LOKASI	POSISI / KONDISI SAMPAH DI ALIRAN SUNGAI / SUMBER SAMPAH
13	Jembatan Maasing	- Muara sungai - Banyak sampah - Sampah berada di sepanjang aliran sungai. Sumber sampah berasal dari permukiman dan berbagai tempat
14	TPI Tumumpa	- Tempat pendaratan dan pelelangan ikan - Banyak sampah - Sampah berasal dari kegiatan pelabuhan dan dari kegiatan di sekitarnya

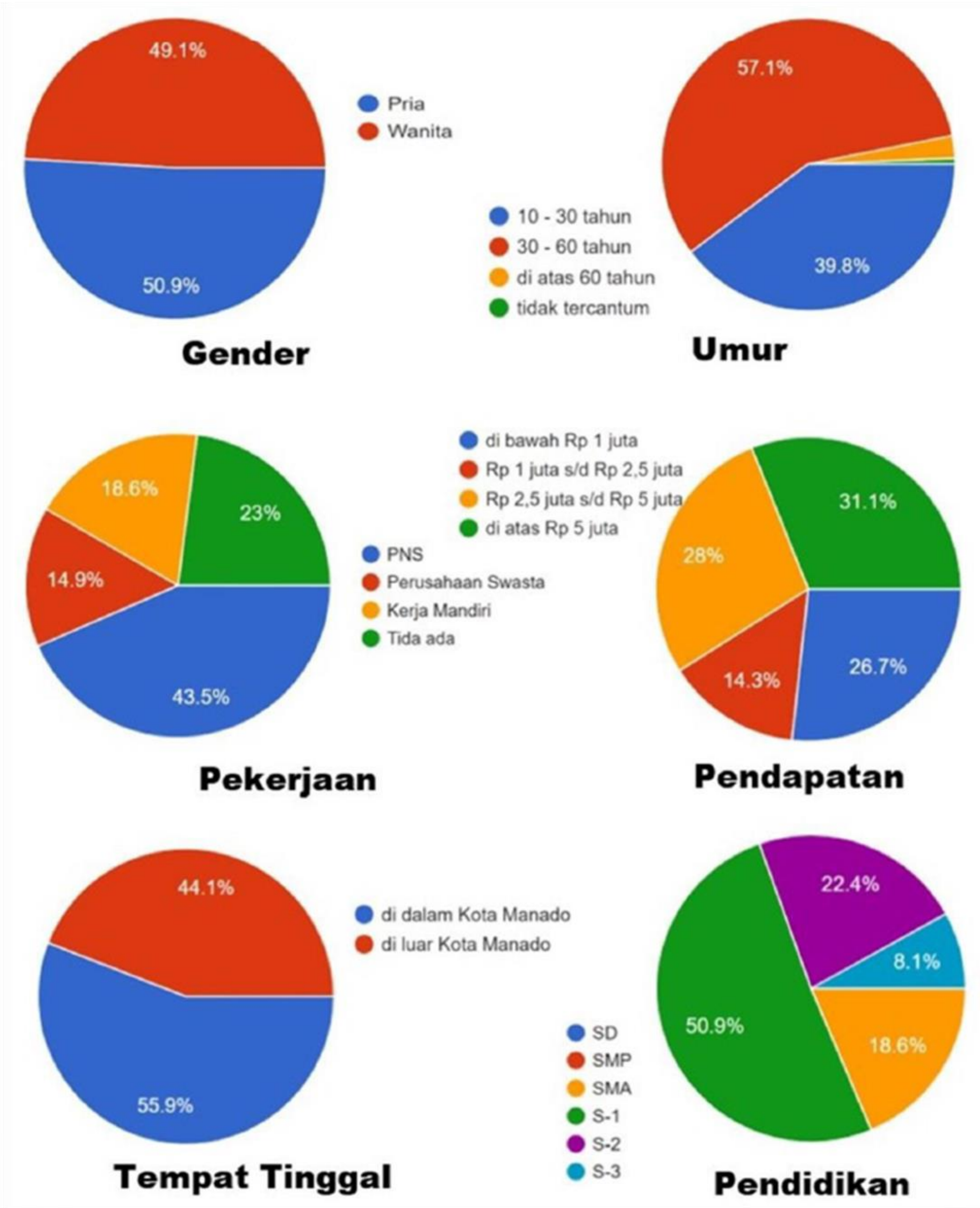
b. Kelembagaan Pemerintah Provinsi Sulawesi Utara

Lembaga di Pemerintah Provinsi Sulawesi Utara yang menangani pengelolaan persampahan, termasuk pengelolaan sampah laut, ialah Dinas Lingkungan Hidup Daerah (DLHD) Provinsi Sulawesi Utara, di bawah kewenangan gubernur. Dinas ini memiliki tujuan dan sasaran dalam menjalankan pemerintahan di tingkat provinsi untuk bagian lingkungan hidup. Tujuan pada tahun 2019-2021, yaitu:

- Memantapkan kenyamanan, keamanan, dan ketertiban masyarakat;
- Melestarikan Lingkungan Hidup melalui upaya-upaya mitigasi perubahan iklim dan pengelolaan keanekaragaman hayati; dan
- Meningkatkan integritas aparatur sipil negara dalam penyelenggaraan pelayanan publik.

Sasaran pada tahun 2019-2021, yaitu:

- Terwujudnya masyarakat yang memiliki pemahaman dan kepatuhan terhadap aturan hukum dan perundangan di bidang lingkungan hidup;
- Terwujudnya Pelestarian lingkungan hidup dan adaptasi perubahan iklim;
- Terwujudnya pelayanan publik di bidang lingkungan hidup yang berdaya saing.



Gambar 3.6. Karakteristik respon dalam studi kesadaran lingkungan

Tabel 3.4
Tingkat Keprihatinan (TP) masyarakat (berbasis perorangan) tentang kondisi lingkungan yang berhubungan dengan sampah (N = 161)

Fokus Pertanyaan	Jawaban (%)			Tidak Menjawab (%)	Modus
	Sangat Prihatin	Prihatin	Tidak Prihatin		
• Keadaan lingkungan disekitar rumah kotor	29,2	70,8	0,0	0,0	
• Banyak sampah di sungai	43,8	55,0	1,2	0,0	
• Banyak sampah di sekitar pinggiran pantai	42,5	57,5	0,0	0,0	
• Pembuangan sampah di sungai	76,3	23,7	0,0	0,0	
• Tidak ada fasilitas tempat sampah di suatu tempat	28,1	69,4	2,5	0,0	
Nilai Agregat	43,9	55,4	0,7	0,0	Prihatin

Kelembagaan DLHD Provinsi Sulut untuk penanganan sampah dan sampah laut ditata dalam bidang Pengelolaan Sampah dan Limbah B3. Tugas bidang ini, berdasarkan Peraturan Gubernur Sulawesi Utara, Nomor 62, Tahun 2016, yang meliputi pengelolaan sampah, limbah B3, dan pengembangan fasilitas tenis, yaitu:

- Penyusunan perencanaan urusan di bidang pengelolaan sampah dan limbah bahan berbahaya dan beracun;
- Pengoordinasian pelaksanaan pengumpulan, pemilahan, penggunaan ulang, pendauran ulang, pengolahan, dan pemrosesan akhir sampah di tempat pembuangan akhir (TPA)/tempat pengolahan sampah terpadu (TPST) regional;
- Perumusan kebijakan pengelolaan sampah dan limbah bahan berbahaya dan beracun;
- Penyelenggaraan urusan pengelolaan sampah;
- Penyelenggaraan urusan limbah bahan berbahaya dan beracun;
- Penyelenggaraan urusan pengembangan fasilitas teknis.

Tabel 3.5
Keinginan masyarakat (basis perorangan) tentang penyelesaian masalah lingkungan, termasuk masalah buangan sampah (N = 161)

Fokus Pertanyaan	Jawaban (%)				Tidak Menjawab (%)	Modus
	Sangat Setuju	Setuju	Kurang Setuju	Tidak Setuju		
Tanggung jawab pemerintah:						
• Pemerintah merupakan satu-satunya pihak yang bertanggung jawab dalam pengelolaan persampahan	7,5	13,7	42,2	36,6	0,0	
• Tidak perlu mengumpulkan dana dari masyarakat untuk kegiatan pengelolaan persampahan	11,3	20,0	56,9	11,9	0,0	
Nilai Agregat	9,4	16,9	49,6	24.3	0,0	Kurang Setuju
Tanggung jawab masyarakat:						
• Masyarakat merupakan satu-satunya pihak yang bertanggung jawab dalam pengelolaan persampahan	11,3	16,3	40,6	31,9	0,0	
• Dana harus dikumpulkan dari masyarakat untuk kegiatan pengelolaan persampahan	3,7	33,8	50,0	12,5	0,0	
Nilai Agregat	7,5	25,1	45,3	22,2	0,0	Kurang Setuju
Tanggung jawab semua pihak:						
• Semua pihak harus bertanggung jawab atas kegiatan pengelolaan persampahan	88,8	10,6	0,6	0,0	0,0	
• Dana dapat dikumpulkan dari masyarakat dan pihak lainnya oleh pemerintah, dan pemerintah akan meningkatkan kondisi dan fasilitas pengelolaan persampahan	25,5	49,7	19,3	5,5	0,0	
Nilai Agregat	57,2	30,2	9,9	2,8	0,0	Sangat Setuju

Dalam pengelolaan sampah, bidang ini menata kelembagaannya ke dalam Seksi Pengelolaan Sampah dengan tugas:

- Menyusun perencanaan urusan pengelolaan sampah;
- Merumuskan kebijakan pengelolaan sampah di provinsi;

- Menetapkan target pengurangan dan penanganan sampah dan prioritas jenis sampah untuk setiap kurun waktu tertentu;
- Mengoordinasikan pelaksanaan pengumpulan, pemilahan, penggunaan ulang, pendauran ulang, pengolahan, dan pemprosesan akhir sampah di TPA/TPST Regional;
- Mengoordinasikan pengangkutan pengolahan dan pemrosesan akhir bila terjadi kondisi kkhusus (bencana alam/non alam atau perselisihan pengelolaan sampah antara Kabupaten/Kota);
- Melaksanakan pembinaan dan penilaian program Adipura.

Tabel 3.6
Degradasi dan dampak sampah laut

JENIS BAHAN	PROSES DEGRADASI & KANDUNGAN	DAMPAK	REFERENSI
Plastik (plastic)	Perubahan ukuran dari makro menjadi mikro		Bhatti *et al.*, 2020
		Perkembangan dan tahapan hidup bulubabi *Paracentrotus lividus*	Bhatti *et al.*, 2020
	Low density polyolefins and PS, textile PET microfibers, polyamide and polypropylene		Castelvetro *et al.*, 2020
Busa plastik (foamed plastic)	Flame retardants (FRs) dan plasticizers, polybrominated diphenyl ethers (PBDEs), organophosphate esters (OPEs),		Cao *et al.*, 2020
	Polystyrene		Chen *et al.*, 2018

Selain seksi tersebut, ditata juga seksi pendukung yang menangani fasilitas teknis, yaitu Seksi Pengembangan Fasilitas Teknis, yang memiliki tugas sebagai berikut:

- Menyusun perencanaan urusan pengembangan fasilitas teknis;
- Mengoordinasikan urusan pengembangan fasilitas teknis;
- Melaksanakan penyediaan sarana/prasarana (sarpras) pengolahan sampah dan limbah bahan berbahaya dan beracun;

- Melaksanakan perencanaan dan pembangunan TPA/TPST Regional;
- Melaksanakan penetapan stasiun peralihan antara (intermediate transfer fascility) dan atau alat angkut untuk pengangkutan dan pengolahan sampah lintas Kabupaten/Kota dalam satu provinsi atau atas usulan dari Kabupaten/Kota;
- Melaksanakan pengembangan teknologi pengelolaan sampah dan limbah bahan berbahaya dan beracun;
- Melaksanakan pengembangan investasi dalam usaha pengelolaan sampah dan limbah bahan berbahaya dan beracun.

c. Kelembagaan Masyarakat

Kelembagaan di masyarakat yang dapat terlibat dalam membantu pengelolaan persampahan, termasuk sampah laut, terdapat dalam 2 bentu, yaitu: kelembagaan yang difasilitasi oleh pemerintah, dan kelembagaan yang mandiri (*indenpendent*). Berikut ini, penjelasan dan contoh mengenai kedua kelembagaan tersebut:

<u>Kelembagaan yang difasilitasi pemerintah</u>. Lembaga seperti ini merupakan lembaga yang keberadaannya (pendirian, proses pelaksanaannya tugas, dan fungsinya) difasilitasi oleh pemerintah, misalnya lembaga pemberdayaan masyarakat. Di Kota Manado, lembaga seperti ini berada di tingkat kelurahan, yang dinamakan Lembaga Pemberdayaan Masyarakat Kelurahan (LPM-K). Menurut Peraturan Daerah (Perda) Kota Manado, Nomor 2, Tahun 2006, tentang Lembaga Pemberdayaan Masyarakat Kelurahan Kota Manado, pendirian lembaga ini memiliki maksud untuk mengotimalkan kelancaran pelaksanaan tugas-tugas pemerintah kelurahan dalam pemberdayaan masyarakat; oleh karena hal inilah, maka lembaga ini pendiriannya difasilitasi oleh pemerintah.

Salah satu fungsi dari LPM-K Kota Manado, yaitu menggali, mendayagunakan, mengembangkan potensi sumberdaya serta keserasian lingkungan hidup. Oleh karena fungsi inilah sehingga LPM-K merupakan lembaga yang strategis dalam pengelolaan persampahan, termasuk sampah laut, di Kota Manado.

<u>Kelembagaan yang mandiri</u>. Lembaga seperti ini merupakan lembaga bukan pemerintah melainkan keberadaanya (pendirian, proses pelaksanaan tugas, dan fungsinya) bersifat mandiri. Oleh sebab itu, lembaga seperti ini disebut Lembaga Swadaya Masyarakat/

LSM (*non-governmental organization*/NGO). Namun, walaupun lembaga seperti mandiri, keberadaannya tetap harus menurut peraturan yang berlaku.

Lembaga Swadaya Masyarakat, pada umumnya didasari atas keiningannya dalam pengelolaan lingkungan hidup yang lestari. Salah satu contoh LSM yang ada di Kota Manado, yaitu LSM Manengkel Solidaritas.

3.11. Hasil Penelitian: Kegiatan Perencanaan dan Pengelolaan Sampah Laut di Kota Manado

Kegiatan perencanaan dan pengelolaan sampah, termasuk sampah laut, di Kota Manado meliputi aspek peraturan dan kebijakan, aspek teknis, dan praktek baik untuk lingkungan (*best environmental practices*), baik yang dilakukan di tingkat Kota Manado maupun di tingkat provisi dan nasional. Untuk aspek peraturan, meliputi:

- Peraturan Daerah Kota Manado, Nomor 07, Tahun 2006, tentang Pengelolaan Persampahan dan Retribusi Pelayanan Kebersihan.
- Peraturan Walikota Manado, Nomor 50, Tahun 2017, tentang Rencana Induk Sistem Pengelolaan Sampah Kota Manado.
- Peraturan Walikota Kota Manado, Nomor 33, Tahun 2018, tentang Pengurangan dan Penanganan Sampah Berbasis Kecamatan Kota Manado.
- Peraturan Walikota Manado, Nomor 24, Tahun 2019, tentang Kebijakan dan Strategi Kota Manado Pengelolaan Sampah Rumah Tangga dan Sampah Sejenis Sampah Rumah Tangga.
- Instruksi Presiden, Nomor 12, Tahun 2016, tentang Gerakan Nasional Revolusi Mental. Salah instruksi adalah Program Gerakan Indonesia Bersih.
- Peratura Presiden Republik Indonesia, Nomor 83, Tahun 2018, tentang Penanganan Sampah Laut.

Untuk aspek kebijakan, meliput:

- Pengurangan sampah dengan penanganan sistem insenerator oleh Walikota Manado.
- Pemasangan kubus apung di beberapa sungai untuk menangkap sampah.

Untuk aspek teknis, meliputi:

- Kewajiban AMDAL bagi rencana kegiatan yang menghasilkan sampah.
- Kewajiban RKL bagi rencana kegiatan yang menghasilkan sampah.
- Kewajiban RPL bagi rencana kegiatan yang menghasilkan sampah.

Kegiatan praktek baik untuk lingkungan (*best environmental practices*), yang telah dan sedang dilakukan di Kota Manado, yaitu:

- Bank sampah (*waste bank*).
- Bersih sampah pantai oleh kelompok, instansi, dan masyarakat.
- Bersih sampah laut oleh kelompok, instansi, dan masyarakat.
- Bersih lingkungan.
- Memilah sampah dari rumah.
- Penghijauan.
- Penggunaan komposter untuk membuat kompos bagi rumah tangga.
- Daur ulang.
- Pelarangan penggunaan kemasan plastik sekali pakai dalam kegiatan.

3.12. Kesimpulan

a. Status pengelolaan sampah laut (*marine litter*) yang dilakukan di darat di Kota Manado belum dilakukan dengan baik.
b. Sampah laut dari jenis bahan ‘plastik’ dan ‘busa plastik’ adalah yang paling lama terurai di laut.
c. Kesadaran lingkungan masyarakat di Kota Manado berhubungan dengan sampah laut (*marine litter*) berada pada tingkatan ‘baik’.
d. Kelembagaan pemerintah Kota Manado dalam mengelola sampah plastik telah ditata secara memadai.
e. Kegiatan perencanaan dan pengelolaan sampah laut di Kota Manado telah dilakukan.

Bagian II:

HASIL PEMANTAUAN SAMPAH LAUT DI KOTA MANADO TAHUN 2020

1. PENDAHULUAN

1.1. Latar Belakang

Teluk Manado (TM) merupakan perairan laut yang terletak di bagian Barat Semenanjung Minahasa, pada bagian Utara Pulau Sulawesi. Di perairan ini terdapat kawasan Taman Nasional Laut Bunaken (TNLB), yang merupakan daerah penyelaman bawah laut dan merupakan destinasi wisata untuk wisatawan domestik dan mancanegara. Secara administratif, perairan ini merupakan bagian dari Kota Manado (ibu kota Provinsi Sulawesi Utara; kota berukuran sedang dengan wilayah seluas 15.726 ha; berpenduduk hampir setengah juta jiwa).

Keberadaan perairan TM sangat erat kaitannya dengan keberadaan Kota Manado. Limbah (cair dan padat) masuk ke perairan ini melalui 5 sungai yang melintasi kota. Limbah cair, yang masuk tanpa mengalami pengolahan terlebih dahulu, telah menyebabkan penurunan kualitas air di daerah muara sungai dan pesisir (Lasut *et al.*, 2005; 2008; 2017). Limbah padat (sampah), yang memenuhi sungai, masuk ke perairan TM (Lasut *et al.*, 2008); akibatnya, sampah tersebut telah menjadi satu dari sekian permasalahan dalam pengelolaan daerah penyelaman di TNLB (Lasut *et al.*, 2017), bahkan di seluruh Perairan Teluk Manado.

Sampah yang masuk ke perairan laut dapat tersebar ke seluruh bagian perairan; dapat berada di dalam kolom air, disebut sebagai sampah laut, dan dapat pula berada di pantai (daerah yang terdedah pada saat air surut terendah), disebut sebagai sampah pantai. Oleh karena sampah ini berasal dari berbagai aktivitas antropogenik dan berbagai penggunaan lahan (Anonimus, 2017), keberadaannnya di ekosistem laut dapat menjadi masalah, bahkan telah menjadi masalah global. Keberadaannya tidak saja menjadi ancaman langsung bagi biota di ekosistem perairan tetapi juga dapat menurunkan kualitas perairan yang dapat berujung pada menurunnya status lingkungan hidup dan kesejahteraan masyarakat (Anonimus, 2017).

Dalam upaya memitigasi dampak sampah di perairan Teluk Manado, khususnya sampah pantai, kegiatan survei pemantauan secara kuantitatif telah dilakukan. Kegiatan ini merupakan bagian dari kegiatan penyusunan data dasar (baseline data) dalam upaya untuk mendukung komitmen Indonesia dalam mengurangi sampah plastik di laut sebesar 70% sampai dengan tahun 2025 (GRI, 2017; Anonimus, 2017). Selain itu, kegiatan ini juga merupakan aksi bersama dalam pertukaran ilmu pengetahuan di mana hal tersebut hendaknya dilakukan dalam upaya menyusun strategi yang efisien secara global (Lasut *et al.*, in press.)

1.2. Tujuan dan Manfaat Pemantauan

Kegiatan pemantauan sampah pantai ini dilakukan dengan tujuan:

- Menentukan persentasi dan kepadatan sampah pantai di Perairan Teluk Manado;
- Mengestimasi jumlah sampah pantai di Perairan Teluk Manado;
- Mengetahui tren jenis sampah pantai.

Hasil penelitian yang diperoleh bermanfaat untuk:

- Sebagai data dasar (baseline data) keberadaan sampah pantai di Teluk Manado;
- Sebagai pembanding bagi daerah lainnya, baik di Indonesia maupun dibelahan bumi lainnya.

1.3. Ruang Lingkup

Ruang lingkup kegiatan ini meliputi survei, pelaksanaan pemantauan sampah pantai, perhitungan dan analisis data. Sampah pantai yang dimaksud dalam kegiatan ini, yaitu sampah yang berasal dari kegiatan perikanan komersil dan rekreasi dan budidaya, perkapalan (termasuk kargo, militer, kapal penumpang dan perahu non-komersil), saluran buangan dari perkotaan, terbawa oleh angin dari daratan, input dari daratan melalui sungai, penggunanaan pantai dan pembuangan sampah secara sembarangan, dan kilang minya lepas pantai (Anonimus, 2017; Cheshire *et al.*, 2009).

1.4. Pendanaan Pemantauan

Kegiatan pemantauan didanai oleh Direktorat Pengendalian Pencemaran dan Kerusakan Pesisir dan Laut, Direktorat Jenderal Pengendalian Pencemaran dan Kerusakan Lingkungan, Kementerian Lingkungan Hidup Dan Kehutanan, Republik Indonesia.

2. PELAKSANAAN KEGIATAN PEMANTAUAN

2.1. Waktu dan Lokasi Pelaksanaan

Survei dilakukan pada tanggal 17 dan 18 Agustus 2020 (Tahap I) dan 6 dan 7 November 2020 (Tahap II). Penentuan waktu survei ini dilakukan berdasarkan kondisi pasang-surut (pasut) lokasi survei di mana, berdasarkan daftar pasut yang diperoleh dari BMKG, pada tanggal tersebut pasut cukup rendah berada pada Pukul 10.00- 13.00. Periode waktu (jam) tersebut merupakan kondisi yang baik untuk melakukan survei.

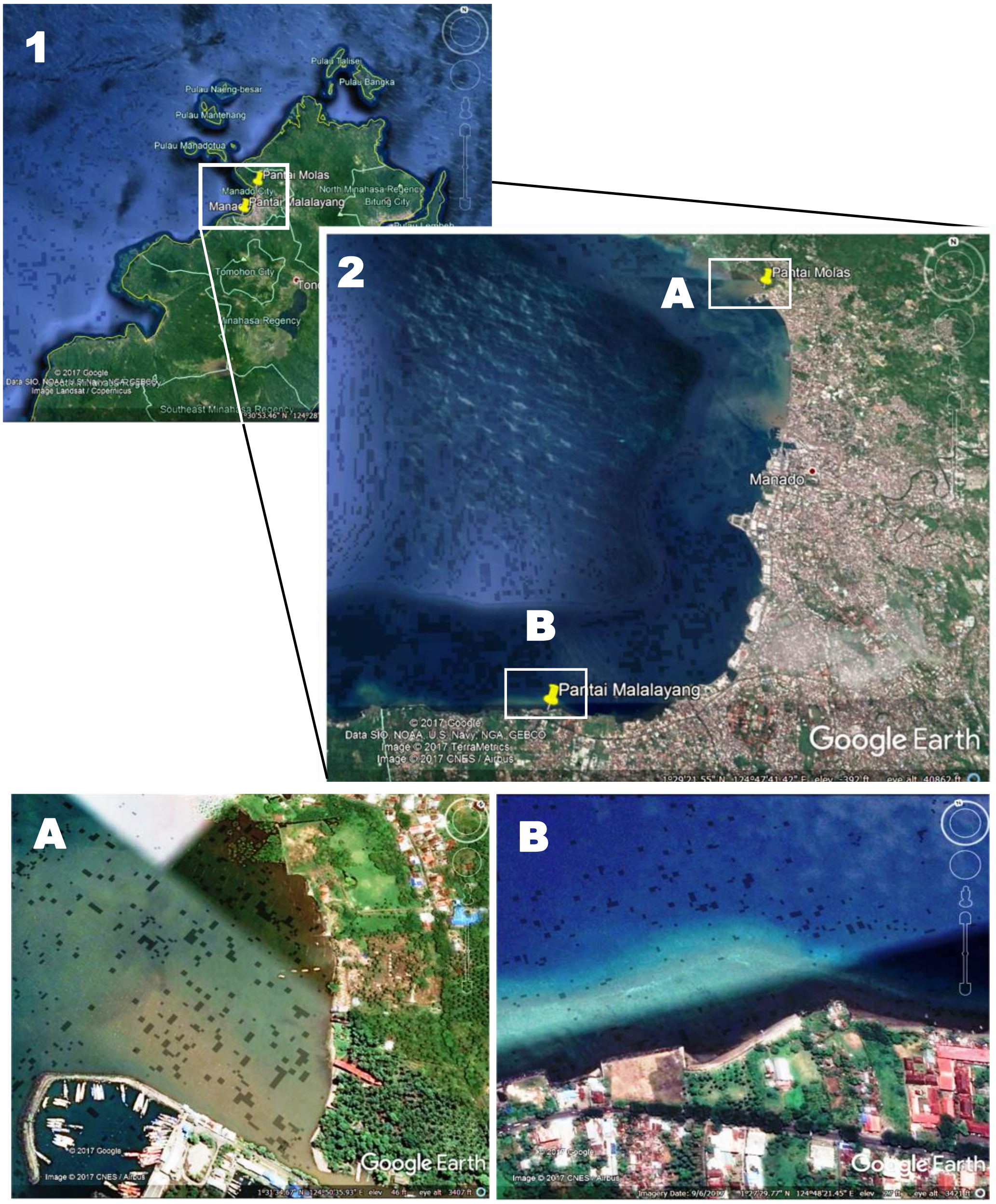
Lokasi pelaksanaan survei untuk Kota Manado ditentukan di perairan Teluk Manado. Pemilihan Lokasi Pengambilan Sampel mengikuti panduan Anonimus (2017) di mana lokasi yang dipilih hendaknya memenuhi kriteria sebagai berikut:

- Dapat diakses sepanjang tahun atau musiman (untuk kesinambungan pemantauan);
- Berpasir atau berkerikil;
- Tidak terdapat pemecah ombak, *jetties*, dermaga atau bangunan-bangunan lainnya;
- Kemiringan landai-moderat;
- Tidak ada aktivitas *clean up* ('bersih-bersih pantai') pada saat yang berdekatan dengan waktu sampling;
- Tidak ada pengelolaan sampah di lokasi tersebut;
- Bukan merupakan habitat sensitif, atau tidak terdapat spesies yang terancam yang mungkin terganggu akibat sampling ini; informasi ini dapat ditanyakan kepada pihak yg berkompeten dalam bidang konservasi.

Berdarkan kriteria di atas, maka 2 (dua) lokasi dipilih, yaitu 1) Pantai Molas/Bailang dan 2) Pantai Malalayang (Gambar 2.1). Lokasi ke-1 masuk dalam kawasan Taman Nasional Bunaken (TNB). Dengan demikian, survei pemantauan sampah laut di Teluk Manado ini merupakan pemantau untuk kawasan TNB juga. Berikut ini deskripsi kedua lokasi pengambilan sampel:

1) Pantai Molas/Bailang

Pantai Molas/Bailang terletak di daerah bagian Utara Kota Manado (sebelah Utara Perairan Teluk Manado). Daerah ini dianggap mewakili daerah urban, karena masuk dalam kawasan perkotaan (Gambar 2.1A). Pantai ini berada di pinggiran muara Sungai Bailang,



Gambar 2.1. Lokasi Pengambilan Sampel di Perairan Teluk Manado, Kota Manado. 1: Semenanjung Minahasa; 2: Teluk Manado; A: Pantai Molas/Bailang; B: Pantai Malalayang.

pada bagian Selatan dan berjarak ± 0.5 km dari jalan raya. Pantai ini bukan merupakan pantai wisata sehingga peruntukannya hanya bagi nelayan untuk memancing dan akses untuk menuju ke laut. Keberadaan sampah di daerah ini, umumnya berasal dari S. Bailang dan daerah laut, yang terdampar.

Survei pemantauan sampah pantai di lokasi ini dilakukan pada 18 Agustus 2020 (Tahap I) dan 6 November 2020 (Tahap II). Karakteristik lokasi dan kondisi sampling, serta deskripsi daerah disekitarnya ditampilkan pada Lampiran 04.

2) Pantai Malalayang

Pantai Malalayang terletak di daerah bagian Selatan Kota Manado (sebelah Selatan Perairan Teluk Manado). Karena daerah ini berada di pinggiran kota, maka dianggap sebagai daerah mewakili daerah sub-urban (Gambar 2.1B). Pantai ini berjarak ± 0.5 km dari jalan raya. Pantai ini bukan merupakan pantai wisata, sehingga peruntukannya bagi nelayan untuk memancing dan akses untuk menuju ke laut. Sumber sampah pada umumnya dari laut, yang terdampar oleh karena arus dan gelombang.

Survei pemantauan sampah pantai di lokasi ini dilakukan pada 17 Agustus 2020 (Tahap I) dan 7 November 2020 (Tahap II). Karakteristik lokasi dan deskripsi daerah disekitarnya ditampilkan pada Lampiran 04.

2.2. Alat, Bahan, dan Metode Pengambilan Sampel

Tabel 2.1 dan 2.2, berturut-turut, menampilkan peralatan dan bahan yang digunakan dalam kegiatan pengamatan, baik pada saat pengambilan sampel maupun pengukuran sampel dan analisis data.

Pengambilan sampel dilakukan menggunakan panduan DPPKPL-DPPKL-KLHK (2020). Berikut ini, secara singkat, tahapan dalam kegiatan pengambilan sampel:

- Pada lokasi survei, dibuat transek sepanjang 100 m, yang sejajar dengan garis pantai, dengan lebar 15 m. Keliling daerah transek ditandai dengan menggunakan tali rafia;
- Transek, yang berjarak 100 m tersebut, di bagi menjadi 5 lajur (tegak lurus dengan garis pantai), masing-masing berjarak 20 m. Pada setiap titik pada lajur ditandai dengan tali rafia dan ditempatkan tongkat berbendera;
- Di dalam setiap lajur 20 m, dibuat sebuah Sub Transek berukuran 5 x 5 m (Gbr. 1.2);
- Di dalam setiap sub transek (berukuran 5 x 5 m) dibuat Sub-sub Transek berukuran 1 x 1 m sebanyak 25 bagian;

Tabel 2.1
Peralatan yang digunakan dalam kegiatan pemantauan sampah pantai di Perairan Teluk Manado, Kota Manado, Provinsi Sulawesi Utara

NAMA ALAT	KEGUNAAN
Klinometer	Mengukur kemiringan lahan
Timbangan	Menimbang berat sampah
Kamera	Membuat Gbr./video
Kalkulator	Mengihitung
GPS	Menentukan koordinat lokasi/titik
Kaca pembesar/loop	Membantu visualisasi objek kecil
Meteran gulung	Menentukan jarak
Serokan	Mengambil sampel dalam wadah pasir/tanah
Saringan/ayakan: ukuran ϕ 0,5 cm; ukuran bingkai 0,5 m	Menyaring sampel
Saringan/ayakan: ukuran ϕ 2,5 cm; ukuran bingkai 0,5 m	Menyaring sampel
Kuadran; ukuran 5 x 5 m	Batasi areal sampling
Kuadrab; ukuran 1 x 1 m	Batas areal sampling
Gunting, Cutter/Pisau lipat	Menggunting, Memotong
Alat tulis menulis (pensil, clip board, spidol permanen)	Menulis, pemberian label

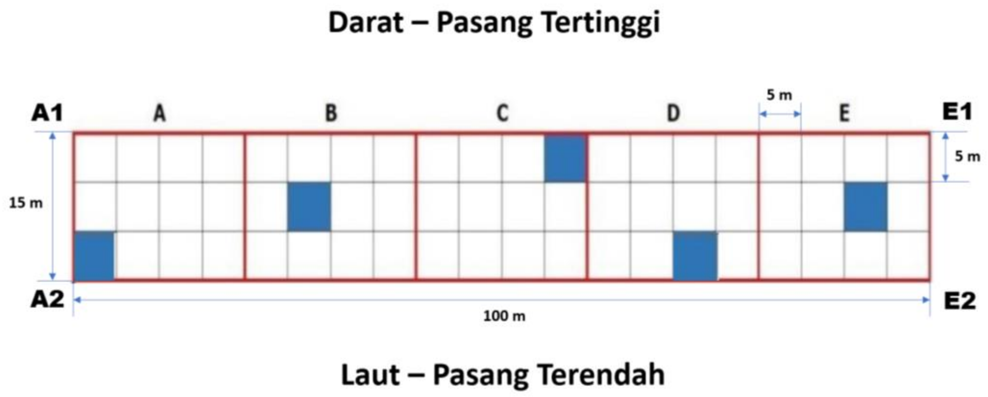
- Semua titik transek terluar dan posisi sub transek ditandai dengan menentukan koordinatnya (Gambar 2.2). Koordinat transek dan sub transek dalam survei ini ditampilkan dalam Tabel 2.3;
- Lima Sub-sub Transek (berukuran 1 x 1 m) ditentukan secara acak (dilakukan dengan cara pengundian);
- Sampling sampah berukuran meso dan makro dilakukan sbb:
    - Sampah ukuran meso, disampling pada semua Sub-sub Kuadran yang telah ditentukan (lihat poin No. 9 di atas). Gunakan saringan berukuran 0,5 cm. Penggalian dilakukan paling dalam 3 cm dari permukaan substrat. Sampah yang disampling dipisahkan menurut nomor sub-sub kuadran 1 x 1 tersebut.
    - Sampah ukuran Makro, disampling pada semua sub-kuadran 5 x 5. Gunakan saringan berukuran 2,5 cm. Sampah yang disampling dipisahkan menurut nomor sub kuadran 5 x 5 tersebut.

Tabel 2.2
Bahan yang digunakan dalam kegiatan pemantauan sampah pantai di Perairan Teluk Manado, Kota Manado, Provinsi Sulawesi Utara

NAMA BAHAN	JENIS BAHAN	KEGUNAAN
Sarung tangan	Karet	Melindungi tangan
Masker	Kasa	Melindungi hidung dan mulut
Karung; ukuran 50-100 kg	Plastik	Mengumpulkan sampah
Terpal	Plastik	
Tongkat pembatas; ukuran 1,5 m	Kayu/ Bambu	Patok pembatas
Bendera; bentuk segitiga; ukuran ½(30 x 30)cm	Kain	Bersama dengan patok pembatas
Tali rafia	Plastik	Penanda batas
Kantong bening; ukuran 3-5 kg	Plastik	Wadah sampel; 50 lembar untuk ukuran makro dan 50 lembar untuk ukuran meso.

- Semua sampah yang telah terkumpul dimasukkan ke dalam wadah plastik, lalu ditutup rapat dan diberi label (nama) menggunakan Spidol Permanen.
- Semua wadah sampel yang telah terisi disimpan dengan baik untuk selanjutnya dilakukan pengklasifikasian (penggolongan) dan perhitungan Jumlah & Berat Sampah.

- Semua wadah sampel yang telah terisi disimpan dengan baik untuk selanjutnya dilakukan pengklasifikasian (penggolongan) dan perhitungan Jumlah & Berat Sampah.
- Pengklasifikasian dilakukan pada semua sampah yang telah terkumpul; dilakukan satu per satu. Pengklasifikasian dilakukan dengan cara memilah;
- Sampah dipilah berdasarkan jenisnya (per jenis) dan dimasukan ke dalam wadah plastik lain yang telah disediakan. Pemilahan dilakukan dengan menggunakan panduan Anonimus (2017);
- Sampah ditimbang (berat) dan dihitung (jumlah) berdasarkan jenisnya
- Data (berat dan jumlah) sampah per jenis di catat ke dalam table yang telah disediakan



Gambar 2.2. Transek, sub transek, dan sub-sub transek untuk pengambilan sampel sampah pantai

2.3. Analisis Data

Data dianalisis menggunakan panduan DPPKPL-DPPKL-KLHK (2020) untuk menghitung Komposisi dan Kepadatan Sampah. Perhitungan tersebut sebagai berikut:

c. Komposisi sampah dihitung persentase (%) berat sampah per jenis per keseluruhan sampah dalam area survei:

$$\text{Komposisi (\%)} = \frac{x}{\Sigma x_1} \times 100;\ x = \text{berat sampah per jenis}$$

d. Kepadatan sampah dihitung dari jumlah sampah per jenis per m^2:

$$\text{Kepadatan (m)} = \frac{\text{jenis}}{\text{Panjang (m) x lebar (m)}}$$

Dalam perhitungan, dibedakan untuk sampah ukuran meso (0,5 – 2,5 cm) dan makro (> 2,5 cm).

Tabel 2.3
Koordinat titik pada transek dan sub transek di lokasi survei

No	Kode Titik	Latitude	Longitude
Pantai Malalayang			
1.	Ujung A1	1.460287°	124.804635°
2.	Ujung A2	1.460421°	124.804586°
3.	Sub transek A	1.460359°	124.804577°
4.	Sub transek B	1.460272°	124.804378°
5.	Sub transek C	1.460235°	124.804100°
6.	Sub transek D	1.460187°	124.803917°
7.	Sub transek E	1.460102°	124.803741°
8.	Ujung E1	1.460047°	124.803731°
9.	Ujung E2	1.460209°	124.803697°
Pantai Molas/Bailang			
1.	Ujung A1	1.525527°	124.842426°
2.	Ujung A2	1.525442°	124.842253°
3.	Sub transek A	1.525483°	124.842363°
4.	Sub transek B	1.525336°	124.842501°
5.	Sub transek C	1.525037°	124.842584°
6.	Sub transek D	1.524889°	124.842617°
7.	Sub transek E	1.524753°	124.842601°
8.	Ujung E1	1.524687°	124.842684°
9.	Ujung E2	1.524635°	124.842551°

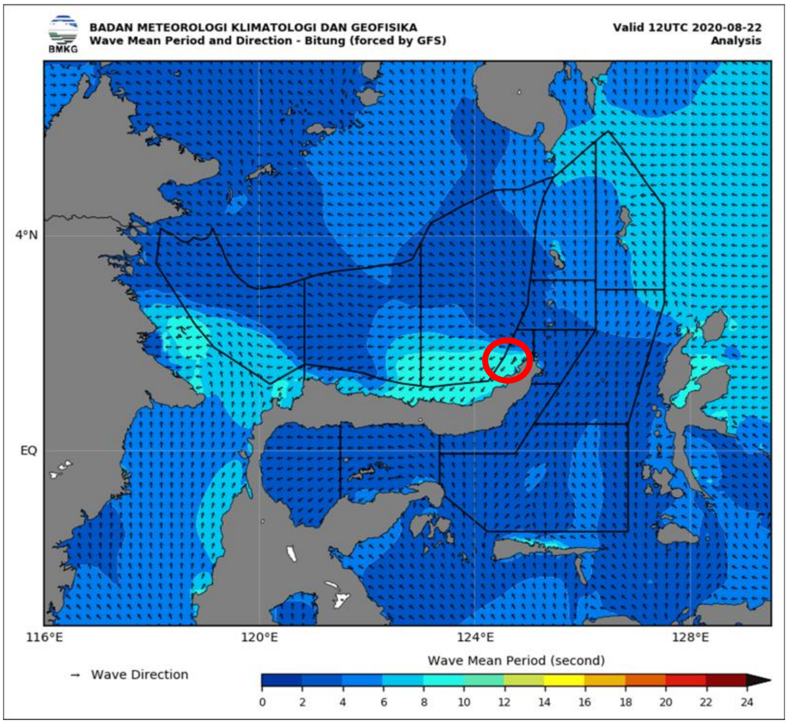
3. HASIL DAN PEMBAHASAN

A. PEMANTAUAN TAHAP I

3a.1. Pemetaan Sumber Pencemar

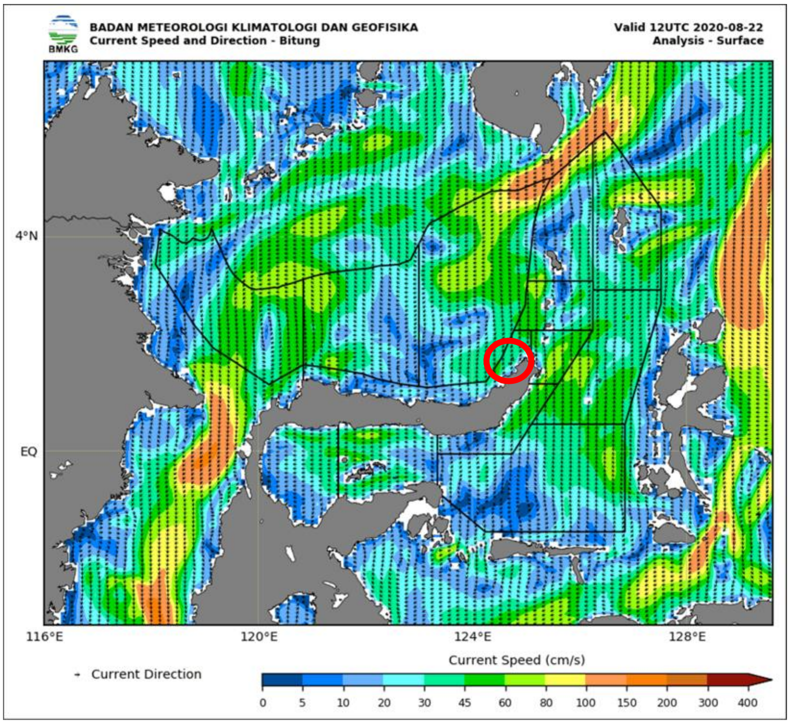
Pengamatan terhadap keberadaan arus laut pada saat sampling dilakukan. Meskipun pendugaan arus laut tidak dapat dilakukan sebelum dan pada saat survei pengambilan sampel, tetapi pendugaan dilakukan setelah survei (4 hari setelah survei, yaitu tanggal 22 Agustus 2020); dengan asumsi, bahwa tidak terjadi perubahan signifikan terhadap parameter tersebut antara pada waktu survei dan pengambilan citra.

Gambar 3a.1 menampilkan citra Arah dan Periode Rerata Gelombang (*Wave Mean Periode and Direction*) pada tanggal 22 Agustus 2020 (BMKG, 2020) di sekitar lokasi pengambilan sampel di perairan



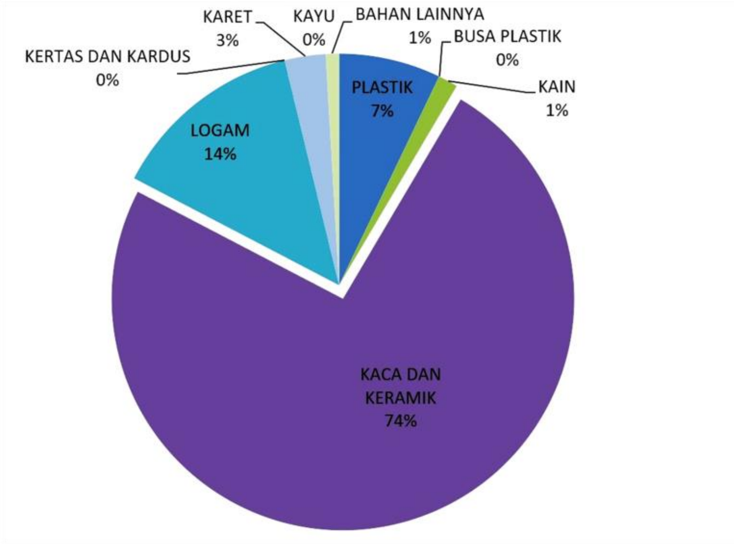
Gambar 3a.1. Periode Arah dan Periode Rerata Gelombang (*Wave Mean Periode and Direction*) di sekitar lokasi pengambilan sampel di Teluk Manado (BMKG, 2020). ⭕ Lokasi Pengambilan Sampel

Teluk Manado. Dari citra tersebut nampak, periode rerata gelombang di sekitar lokasi pengambilan sampel berkisar 8-10 detik dengan arah gelombang (*wave direction*) ke Tenggara. Gambar 3a.2 menampilkan citra Kecepatan dan Arah Arus (*Current Speed and Direction*) pada tanggal 22 Agustus 2020 (BMKG) di sekitar lokasi pengambilan sampel di perairan Teluk Manado. Nampak, kecepatan arus di sekitar lokasi pengambilan sampel berkisar 20-30 cm/detik, dengan arah arus ke Timur Laut, menyusuri pantai.



Gambar 3a.2. Kecepatan dan Arah Arus (*Current Speed and Direction*) di sekitar lokasi pengambilan sampel di Teluk Manado (BMKG, 2020).
○ Lokasi Pengambilan Sampel

Berdasarkan arah arus di Teluk Manado (Gbr. 3a.2), keberadaan sampah laut di Pantai Malalayang diduga berasal dari daerah bagian Selatan. Di daerah pesisir daratan Teluk Manado bagian Selatan, umumnya merupakan daerah rural (pedesaan) dengan jumlah penduduk yang relatif sedikit. Namun, pada umumnya desa-desa tersebut berada di pinggiran pantai. Keberadaan sampah laut di Pantai Molas/Bailang diduga berasal dari sungai-sungai di bagian Selatan, yaitu 4 sungai besar yang melintasi Kota Manado dari dataran tinggi.



Gambar 3a.3. Komposisi sampah pantai berukuran makro (> 2,5 cm) berdasarkan berat jenis bahan di Pantai Malalayang, Kota Manado, pada bulan Agustus 2020

Keempat sungai tersebut, yaitu S. Tondano, S. Malalayang, S. Sario, dan S. Bailang. Lokasi pengambilan sampel di Pantai Molas/Bailang berada bersebelahan dengan S. Bailang.

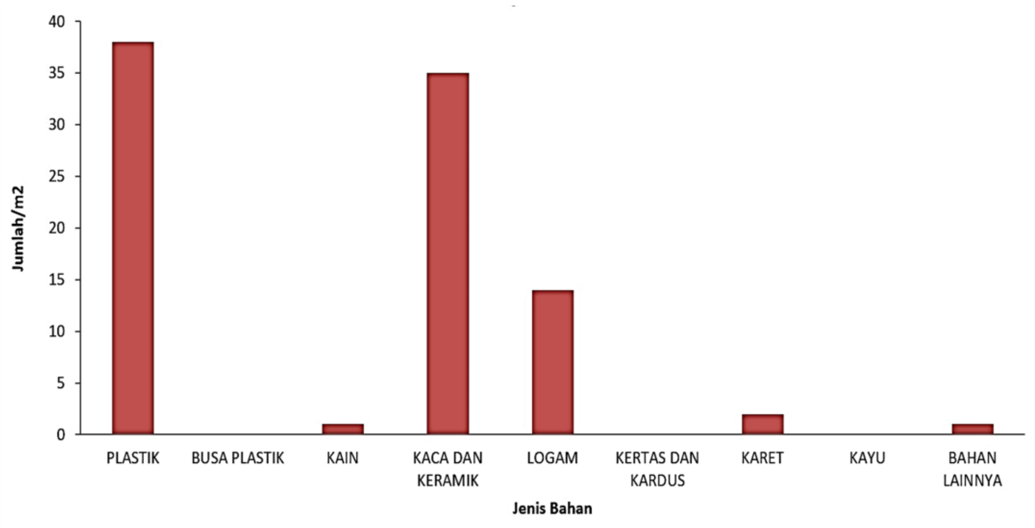
Keberadaan sampah pantai di Pantai Molas/Bailang merupakan *input* yang besar (*loading*) ke Teluk Manado dari Kota Manado dan daerah dataran tinggi di sekitarnya. Hal ini memberi dampak yang signifikan bagi keberadaan sampah laut di Teluk Manado, yang diduga dapat memberikan dampak lebih besar lagi ke Kawasan Taman Nasional Bunaken (TNB).

3a.2. Analisis Data dan Pembahasan

3a.2.1. Sampah Pantai Malalayang

a. Sampah makro

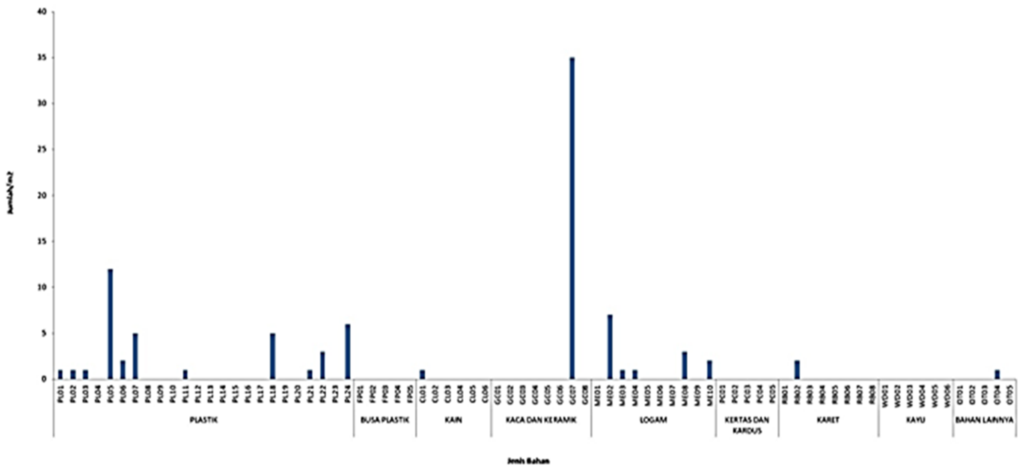
Gambar 3a.3, Gbr. 3a.4, dan Gbr. 3a.5 menampilkan komposisi sampah pantai berukuran makro (> 2,5 cm) di Pantai Malalayang pada bulan Agustus 2020, berturut-turut berdasarkan berat jenis bahan, jumlah jenis bahan, dan jumlah spesifikasi jenis. Nampak pada Gbr. 3a.3, berat tertinggi sampah pantai berukuran makro yaitu jenis kaca dan keramik (74%), kemudian diikuti oleh jenis logam (14%). Sementara itu, jenis terbanyak berdasarkan jumlah yaitu jenis plastik dan diikuti oleh kaca dan keramik (Gbr. 3a.4). Sedangkan berdasarkan jumlah



Gambar 3a.4. Komposisi sampah pantai berukuran makro (> 2,5 cm) berdasarkan jumlah jenis bahan di Pantai Malalayang, Kota Manado, pada bulan Agustus 2020

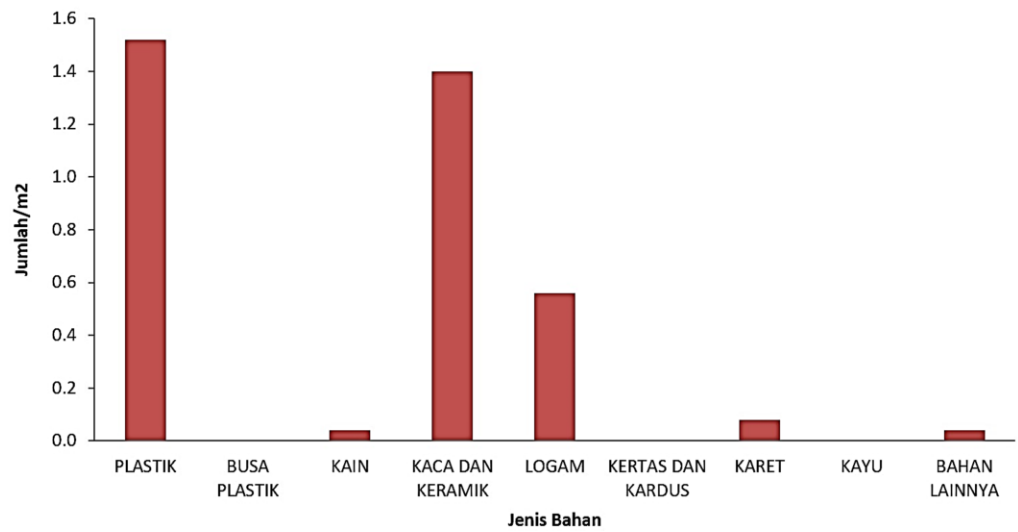
spesifikasi jenis bahan, bahan kaca dan keramik merupakan jenis yang terbanyak, khususnya pecahan kaca dan keramik (GC07) (Gbr. 3a.5).

Gambar 3a.6 dan Gbr. 3a.7 menampilkan kepadatan sampah pantai berukuran makro di Pantai Malalayang, berturut-turut berdasarkan jenis bahan dan spesifikasi jenis bahan. Nampak, sampah



Gambar 3a.5. Komposisi sampah pantai ukuran makro (> 2,5 cm) berdasarkan jumlah spesifikasi jenis bahan di Pantai Malalayang, Kota Manado, pada bulan Agustus 2020

pantai bahan plastik merupakan jenis yang terpadat, dan diikuti oleh kaca dan keramik (Gbr. 3a.6). Namun, spesifikasi jenis bahan yang tertinggi yaitu kaca dan keramik, khususnya pecahan kaca dan keramik (GC07); sedangkan jenis bahan plastik yang tertinggi yaitu paket peralatan minuman dan wadah makanan (PL05) (Gbr. 3a.7).

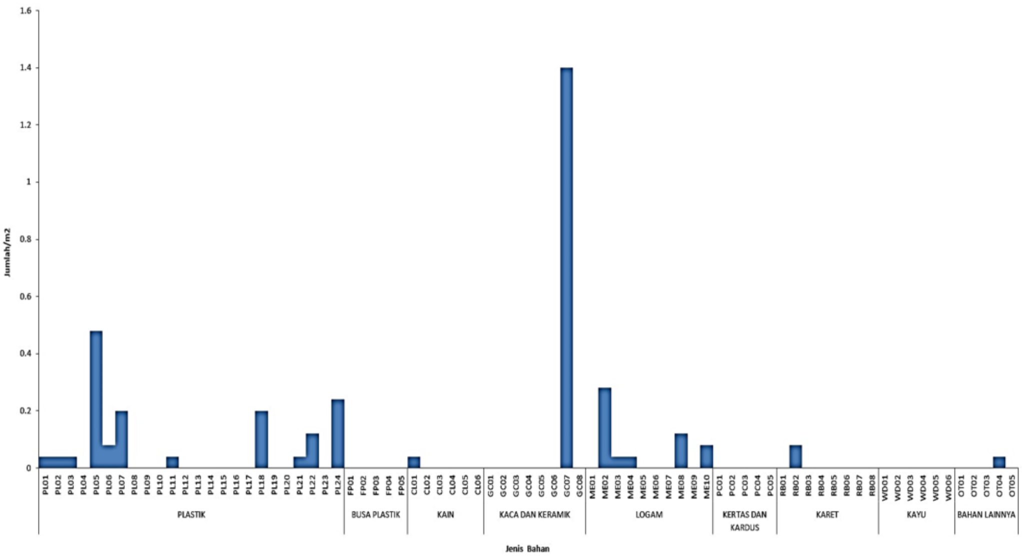


Gambar 3a.6. Kepadatan sampah pantai ukuran makro (> 2,5 cm) berdasarkan jenis bahan di Pantai Malalayang, Kota Manado, pada bulan Agustus 2020

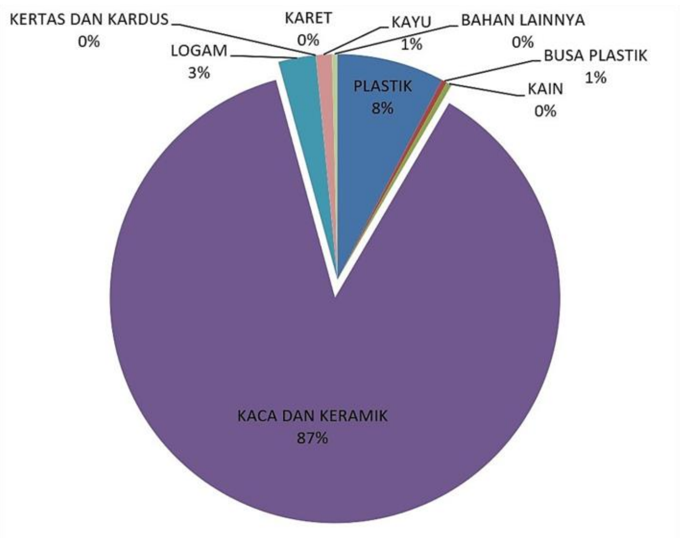
b. Sampah meso

Gambar 3a.8, Gbr. 3a.9, dan Gbr. 3a.10 menampilkan komposisi sampah pantai berukuran meso (5 mm-2,5 cm) di Pantai Mala pada bulan Agustus 2020, berturut-turut berdasarkan berat jenis bahan, jumlah jenis bahan, dan jumlah spesifikasi jenis. Jenis bahan kaca dan keramik memiliki komposisi tertinggi (87%), yang diikuti oleh jenis bahan plastik (8%) (Gbr. 3a.8). Jenis bahan kaca dan keramik juga memiliki komposisi jumlah yang terbanyak (Gbr. 3a.9); dengan spesifikasi jenis yang terbanyak yaitu pecahan kaca dan keramik (GC07) (Gbr. 3a.10).

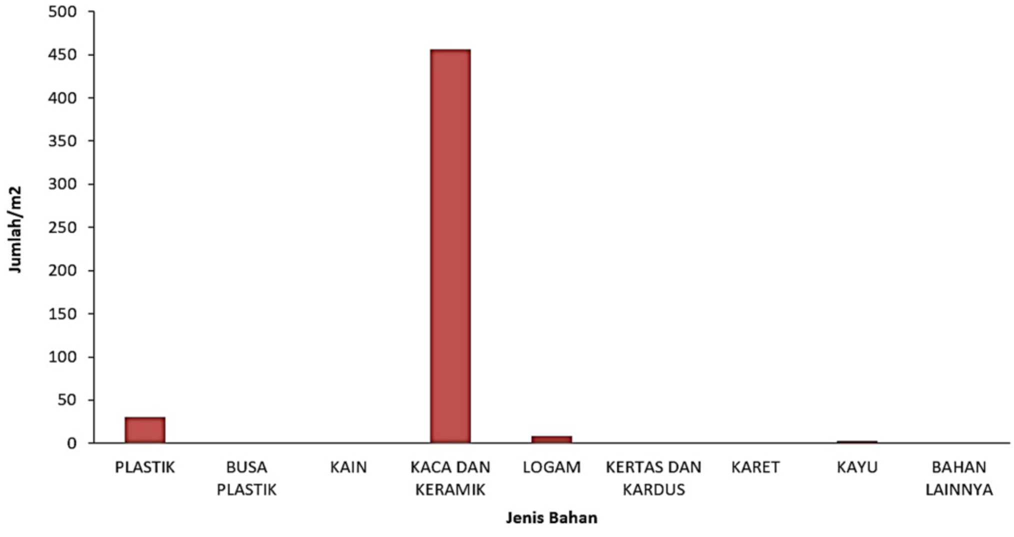
Gambar 3a.11 dan Gbr. 3a.12 menampilkan kepadatan sampah pantai berukuran meso di Pantai Malalayang berdasarkan jenis bahan dan spesifikasi jenis bahan. Jenis bahan kaca dan keramik memiliki kepadatan yang tertinggi (Gbr. 3a.11) dengan spesifikasi jenis pecahan kaca dan keramik (GC07) yang terbanyak (Gbr. 3a.12).



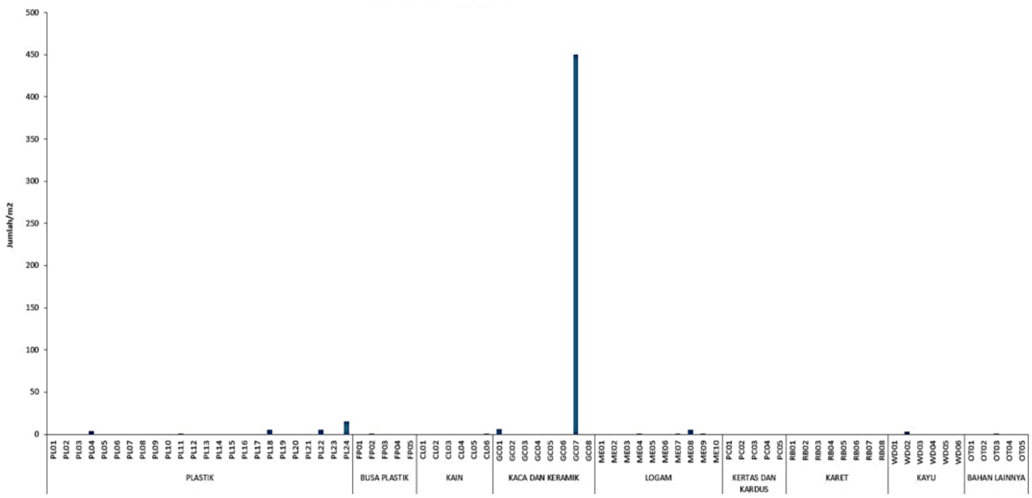
Gambar 3a.7. Kepadatan sampah pantai ukuran makro (> 2,5 cm) berdasarkan spesifikasi jenis bahan di Pantai Malalayang, Kota Manado, pada bulan Agustus 2020



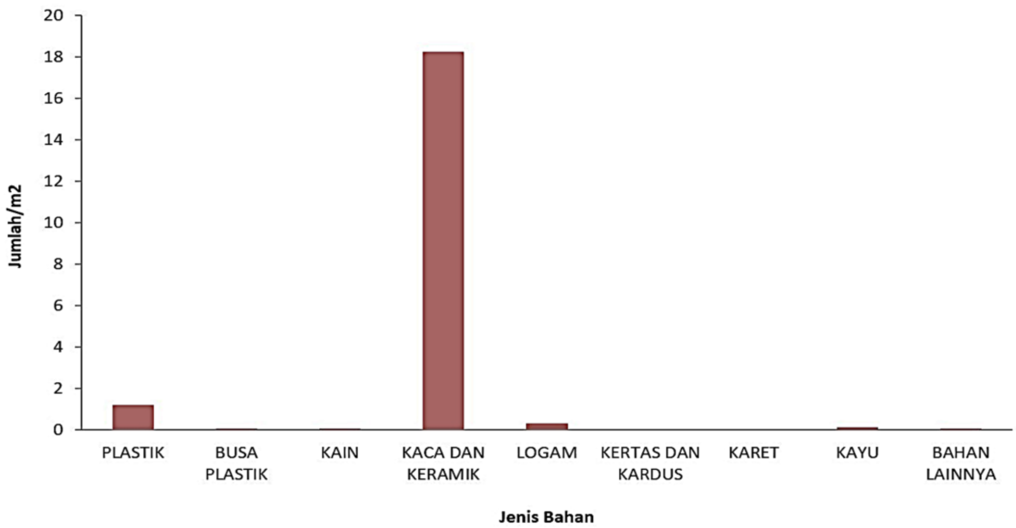
Gambar 3a.8. Komposisi sampah pantai berukuran meso (5 mm-2,5 cm) berdasarkan berat jenis bahan di Pantai Malalayang, Kota Manado, pada bulan Agustus 2020



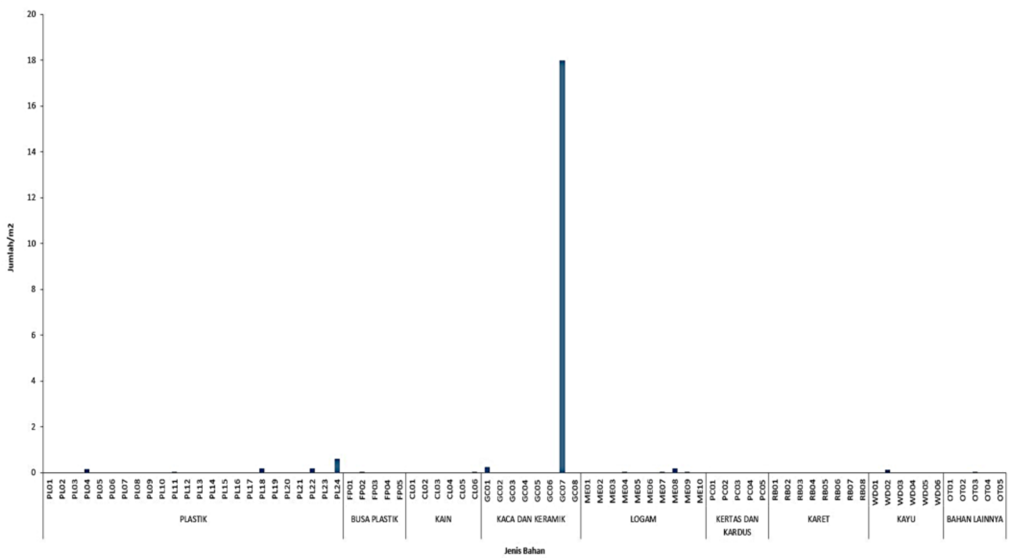
Gambar 3a.9. Komposisi sampah pantai berukuran meso (5 mm-2,5 cm) berdasarkan jumlah jenis bahan di Pantai Malalayang, Kota Manado, pada bulan Agustus 2020



Gambar 3a.10. Komposisi sampah pantai ukuran meso (5 mm-2,5 cm) berdasarkan jumlah spesifikasi jenis bahan di Pantai Malalayang, Kota Manado, pada bulan Agustus 2020



Gambar 3a.11. Kepadatan sampah pantai ukuran meso (5 mm-2,5 cm) berdasarkan jenis bahan di Pantai Malalayang, Kota Manado, pada bulan Agustus 2020

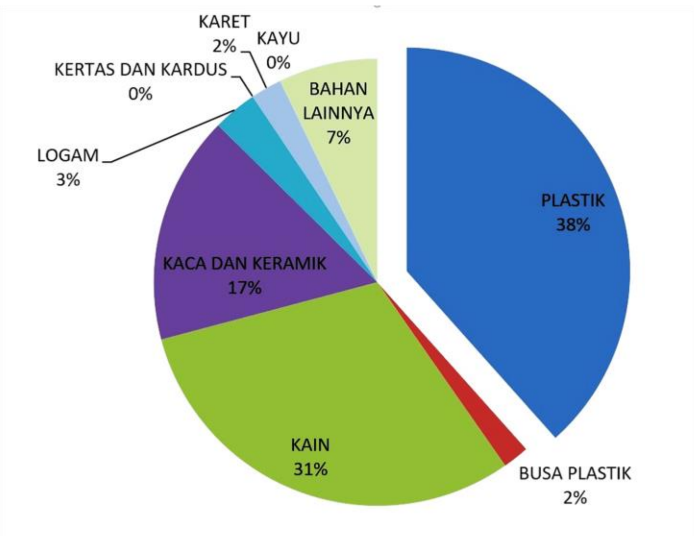


Gambar 3a.12. Kepadatan sampah pantai ukuran meso (5 mm-2,5 cm) berdasarkan spesifikasi jenis bahan di Pantai Malalayang, Kota Manado, pada bulan Agustus 2020

3a.2.2. Sampah Pantai Molas/Bailang

a. Sampah makro

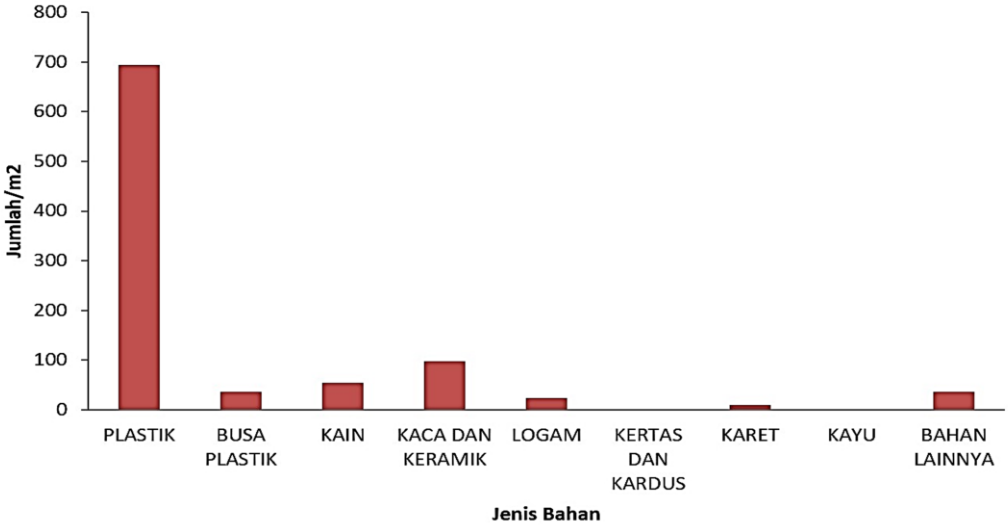
Gambar 3a.13, Gbr. 3a.14, dan Gbr. 3a.15 menampilkan komposisi sampah pantai berukuran makro (> 2,5 cm) di Pantai Molas/Bailang pada bulan Agustus 2020, berturut-turut berdasarkan berat jenis bahan, jumlah jenis bahan, dan jumlah spesifikasi jenis. Tiga jenis bahan yang memiliki komposisi tertinggi, yaitu plastik (38%), kain (31%), dan kaca dan keramik (17%). Di samping itu, bahan lainnya juga cukup tinggi (7%) (Gbr. 3a.13). Untuk komposisi berdasarkan jumlah, jenis bahan plastik merupakan yang tertinggi, dan diikuti oleh jenis kaca dan keramik, kain, serta bahan lainnya (Gbr. 3a.14). Komposisi sampah tertinggi berdasarkan spesikasi jenis bahan plastik, yaitu bahan plastik lainnya (PL24) dan paket peralatan minuman dan wadah makanan (PL05). Kemudian dari jenis bahan kaca dan keramik, yaitu pecahan kaca dan keramik (GC07) (Gbr. 3a.15).



Gambar 3a.13. Komposisi sampah pantai berukuran makro (> 2,5 cm) berdasarkan berat jenis bahan di Pantai Molas/Bailang, Kota Manado, pada bulan Agustus 2020

Gambar 3a.16 dan Gbr. 3a.17 menampilkan kepadatan sampah pantai berukuran makro di Pantai Molas/Bailang pada bulan Agustus 2020, berturut-turut berdasarkan jenis dan spesifikasi bahan. Kepadatan sampah tertinggi didominasi oleh jenis bahan plastik, dan kemudian kaca dan keramik, serta kain dan bahan lainnya (Gbr. 3a.16).

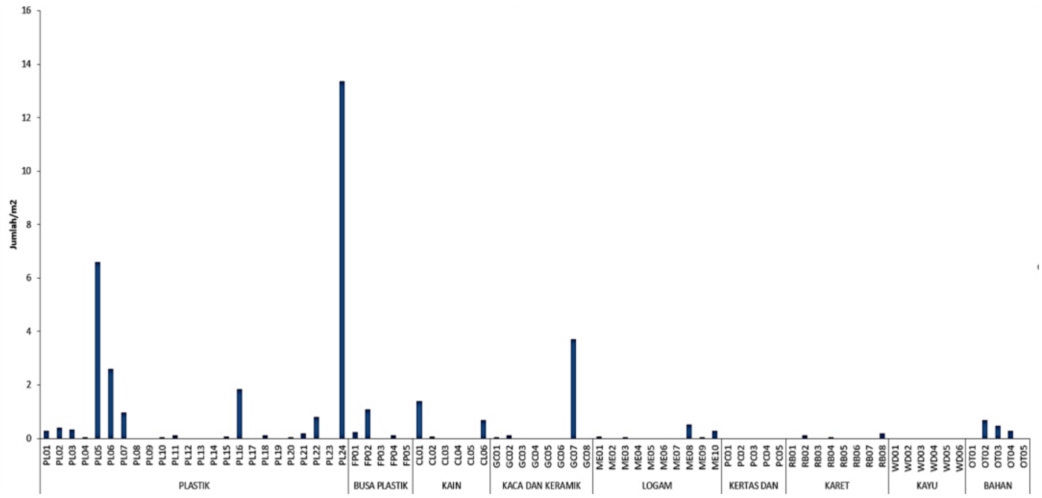
Jenis bahan plastik tertinggi, yaitu spesifikasi bahan plastik lainnya (PL24) dan paket peralatan minuman dan wadah makanan (PL05). Kepadatan jenis bahan plastik diikuti oleh jenis bahan kaca dan keramik, khususnya jenis pecahan kaca dan keramik (GC07) (Gbr. 3a.17).



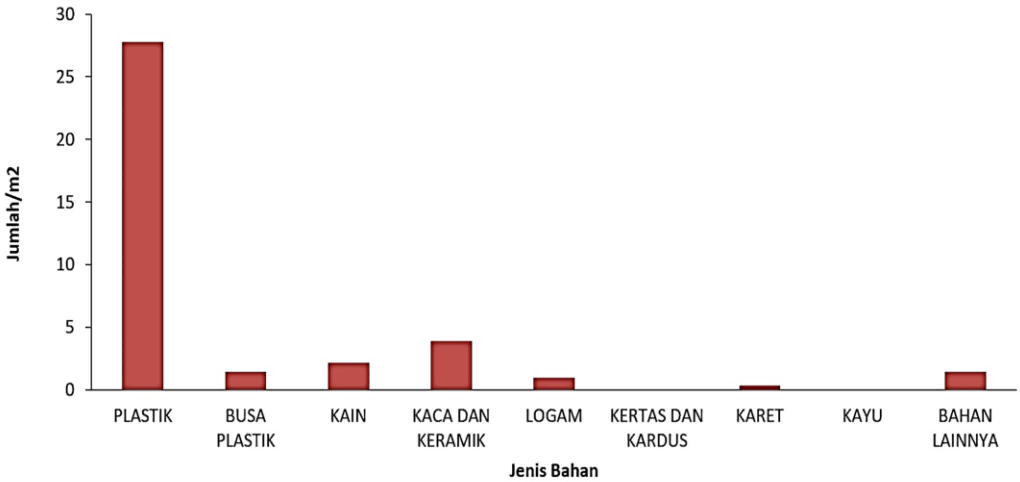
Gambar 3a.14. Komposisi sampah pantai berukuran makro (> 2,5 cm) berdasarkan jumlah jenis bahan di Pantai Molas/Bailang, Kota Manado, pada bulan Agustus 2020

b. Sampah meso

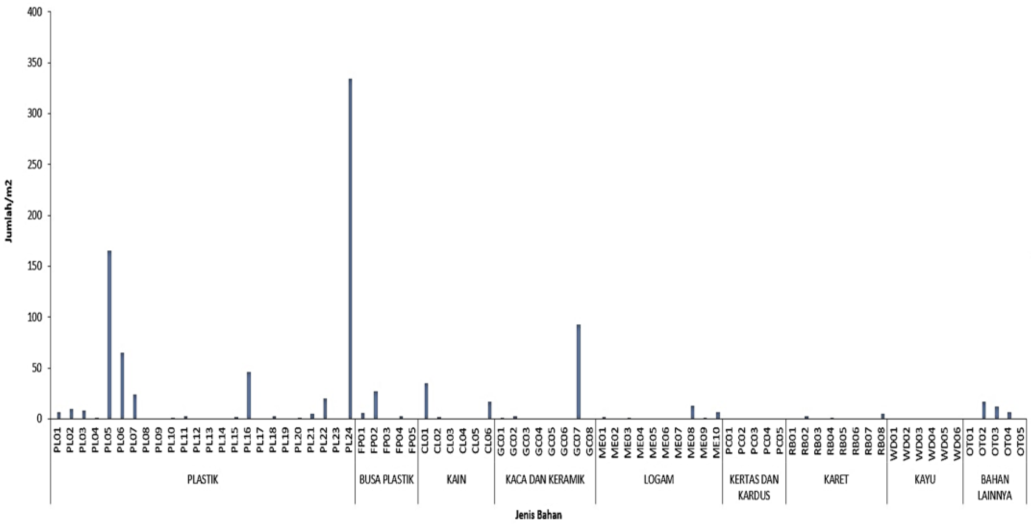
Gambar 3a.18, Gbr. 3a.19, dan Gbr. 3a.20 menampilkan komposisi sampah pantai berukuran meso (5 mm-2,5 cm) di Pantai Molas/Bailang pada bulan Agustus 2020, berturut-turut berdasarkan berat jenis bahan, jumlah jenis bahan, dan jumlah spesifikasi jenis. Nampak, 3 jenis bahan dengan komposisi tertinggi yaitu plastik (44%), kaca dan keramik (25%), dan logam (22%) (Gbr. 3a.18). Hal ini berbeda dengan keberadaan sampah pantai berukuran makro (Gbr. 3a.13). Jumlah terbanyak juga didominasi, berturut-turut, oleh jenis bahan plastik, kaca dan keramik, dan logam (Gbr. 3a.19). Jumlah jenis bahan tertinggi, berdasarkan spesifikasi, untuk jenis plastik, yaitu bahan plastik lainnya (PL24) dan terpal (terpal atau kantong plastik anyaman lainnya, bungkus palet) (PL16); untuk jenis kaca dan keramik, yaitu pecahan kaca dan keramik (GC07); dan untuk jenis logam, yaitu serpihan logam (ME08) (Gbr. 3a.20).



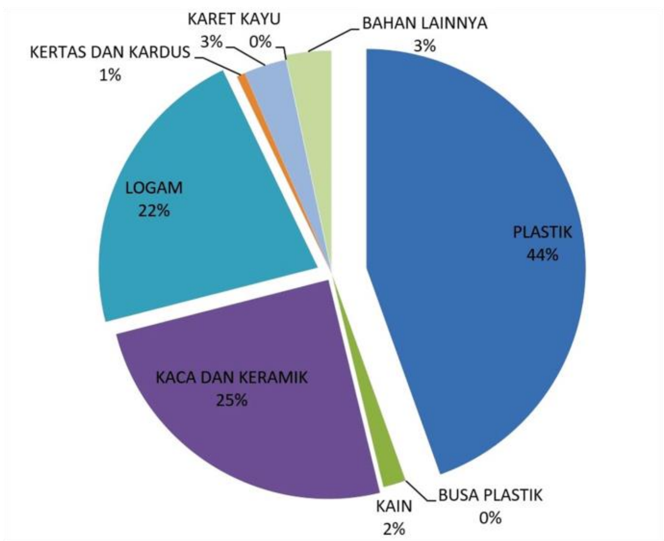
Gambar 3a.15. Komposisi sampah pantai ukuran makro (> 2,5 cm) berdasarkan jumlah spesifikasi jenis bahan di Pantai Molas/Bailang, Kota Manado, pada bulan Agustus 2020



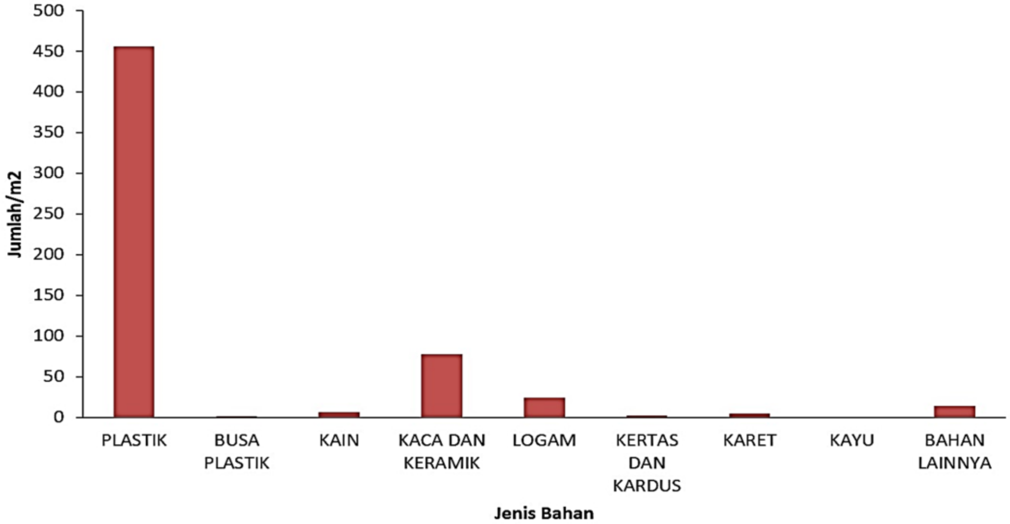
Gambar 3a.16. Kepadatan sampah pantai ukuran makro (>2,5 cm) berdasarkan jenis bahan di Pantai Molas/Bailang, Kota Manado, pada bulan Agustus 2020



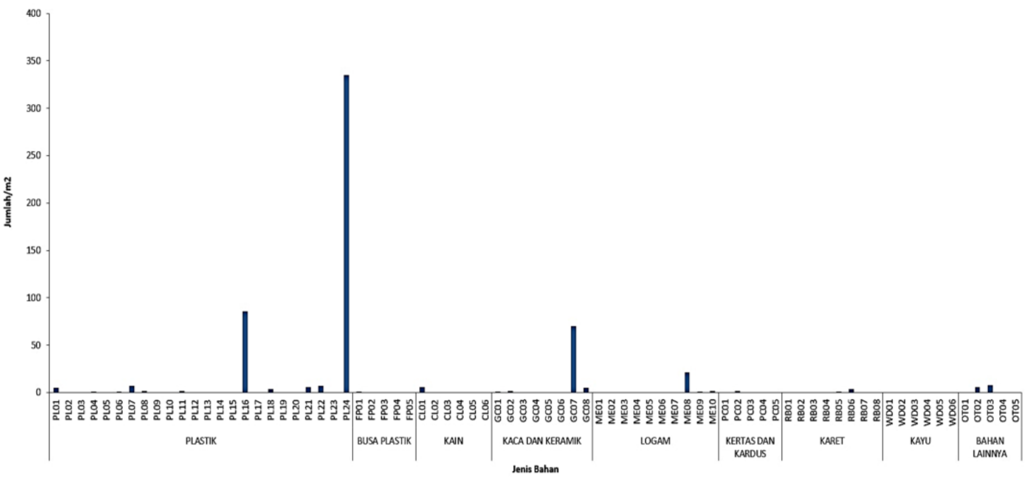
Gambar 3a.17. Kepadatan sampah pantai ukuran makro (> 2,5 cm) berdasarkan spesifikasi jenis bahan di Pantai Molas/Bailang, Kota Manado, pada bulan Agustus 2020



Gambar 3a.18. Komposisi sampah pantai berukuran meso (5 mm-2,5 cm) berdasarkan berat jenis bahan di Pantai Molas/Bailang, Kota Manado, pada bulan Agustus 2020

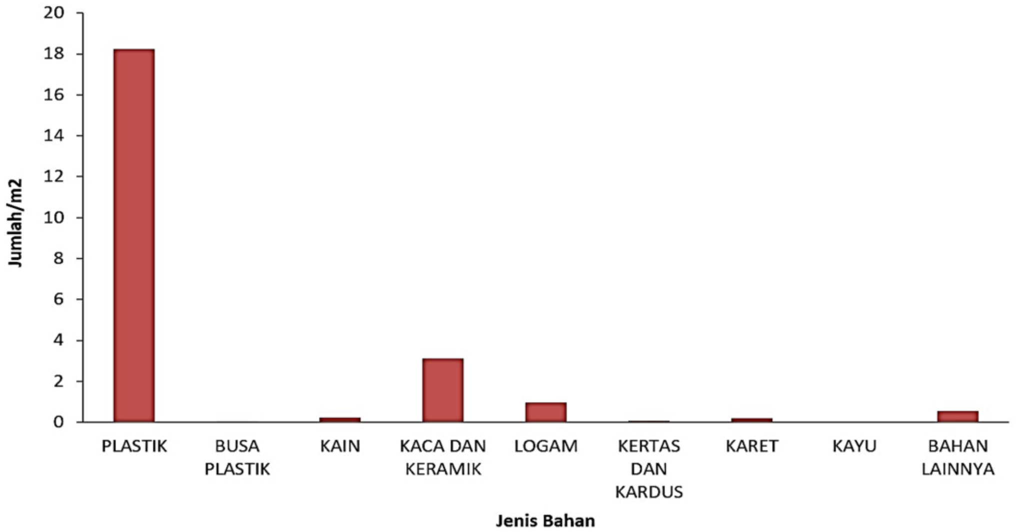


Gambar 3a.19. Komposisi sampah pantai berukuran meso (5 mm-2,5 cm) berdasarkan jumlah jenis bahan di Pantai Molas/Bailang, Kota Manado, pada bulan Agustus 2020



Gambar 3a.20. Komposisi sampah pantai ukuran meso (5 mm-2,5 cm) berdasarkan jumlah spesifikasi jenis bahan di Pantai Molas/Bailang, Kota Manado, pada bulan Agustus 2020

Gambar 3a.21 dan Gbr. 3a.22 menampilkan kepadatan sampah pantai berukuran meso di Pantai Molas/Bailang, berturut-turut berdasarkan jenis bahan dan spesifikasi jenis bahan. Sampah pantai terpadat yaitu jenis bahan plastik, kemudian diikuti oleh kaca dan keramik dan logam (Gbr. 3a.21). Spesifikasi plastik yang memiliki kepadatan tertinggi yaitu bahan plastik lainnya (PL24) dan terpal (PL16). Sedangkan spesifikasi bahan kaca dan keramik yang memiliki kepadatan tertinggi, yaitu pecahan kaca dan keramik (GC07) (Gbr. 3a.22).

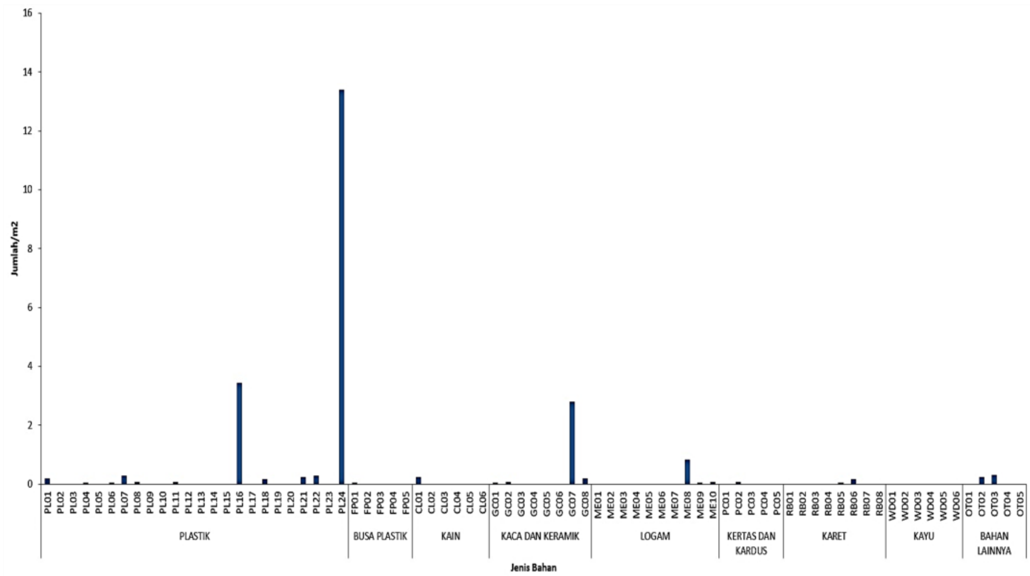


Gambar 3a.21. Kepadatan sampah pantai ukuran meso (5 mm-2,5 cm) berdasarkan jenis bahan di Pantai Molas/Bailang, Kota Manado, pada bulan Agustus 2020

3a.2.3. Sampah Kota Manado

Tabel 3a.1 menampilkan range kepadatan (jumlah/m^2) sampah pantai di Kota Manado pada bulan Agustus 2020, baik sampah berukuran makro maupun meso. Dari 9 jenis yang ditemukan, kepadatan sampah pantai tertinggi (27,8 potong/m^2 dan 18,24 potong/m^2) ditemukan pada jenis bahan plastik, berturut-turut berukuran makro dan meso.

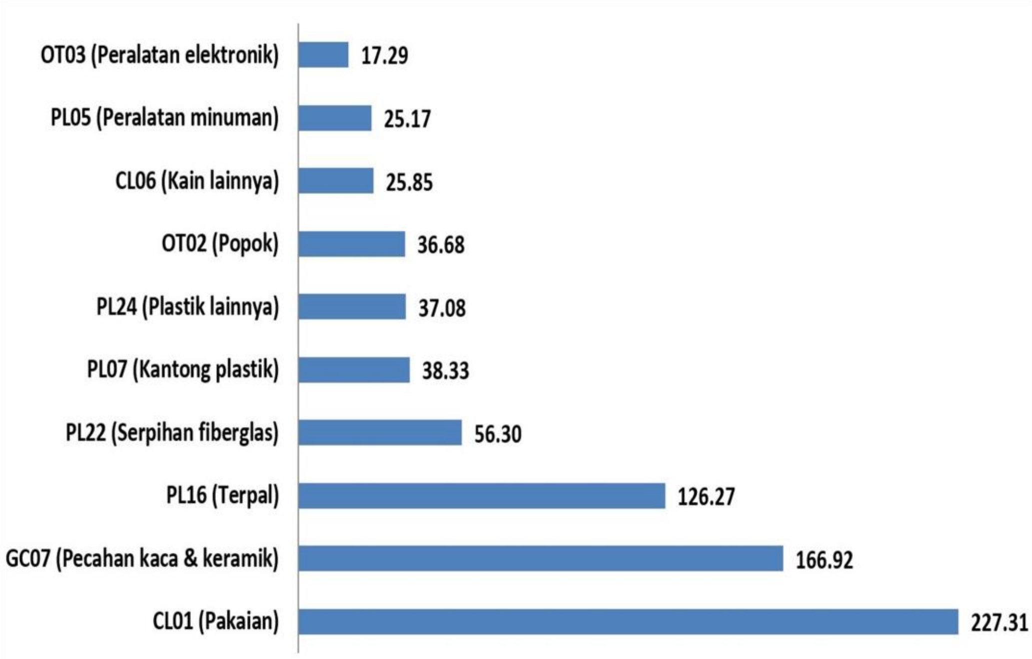
Gambar 3a.23 menampilkan 'Top 10' sampah pantai Kota Manado pada bulan Agustus 2020 (gr/m^2). Jenis pakaian (CL01) merupakan sampah pantai tertinggi (227,31 gr/m^2); jenis bahan plastik, khususnya kantong plastik (PL07) menempati urutan ke-5 (38,33 gr/m^2).



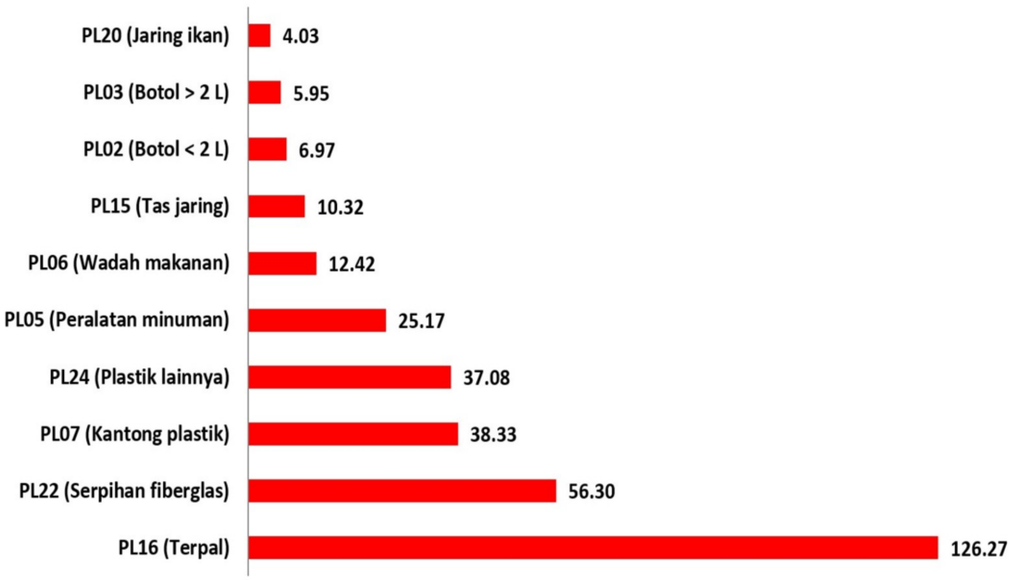
Gambar 3a.22. Kepadatan sampah pantai ukuran meso (5 mm-2,5 cm) berdasarkan spesifikasi jenis bahan di Pantai Molas/Bailang, Kota Manado, pada bulan Agustus 2020

Tabel 3a.1
Range kepadatan (jumlah/m^2) sampah pantai di Kota Manado pada bulan Agustus 2020

No	Jenis Sampah	Range Kepadatan (Jumlah/m^2)	
		Makro	Meso
1.	Plastik	1,52 - 27,8	1,2 - 18,24
2.	Busa Plastik	0,00 - 1,44	0,04 - 0,04
3.	Kain	0,04 - 2,16	0,04 - 0,24
4.	Kaca Dan Keramik	1,40 - 3,88	3,12 - 18,24
5.	Logam	0,56 - 0,96	0,32 - 0,96
6.	Kertas Dan Kardus	0,00 - 0,00	0,00 - 0,08
7.	Karet	0,08 - 0,36	0,00 - 0,20
8.	Kayu	0,00 - 0,00	0,00 - 0,12
9.	Bahan Lainnya	0,04 - 1,44	0,04 - 0,56



Gambar 3a.23. Top 10 sampah pantai Kota Manado pada bulan Agustus 2020 (gr/m^2)



Gambar 3a.24. Top 10 Sampah pantai dari jenis bahan plastik Kota Manado pada bulan Agustus 2020 (gr/m^2)

Khusus jenis bahan plastik, 'Top 10' sampah pantai dari jenis ini di Kota Manado pada bulan Agustus 2020 (gr/m^2) ditampilkan pada Gbr. 3a.24. Nampak, plastik terpal (PL16) memiliki jumlah (berat) tertinggi, yaitu sebesar 126,27 gr/m^2. Sedangkan, kantong plastik (PL07) berada pada urutan ke-3 dengan jumlah (berat) sebesar 38,33 gr/m^2.

B. PEMANTAUAN TAHAP II

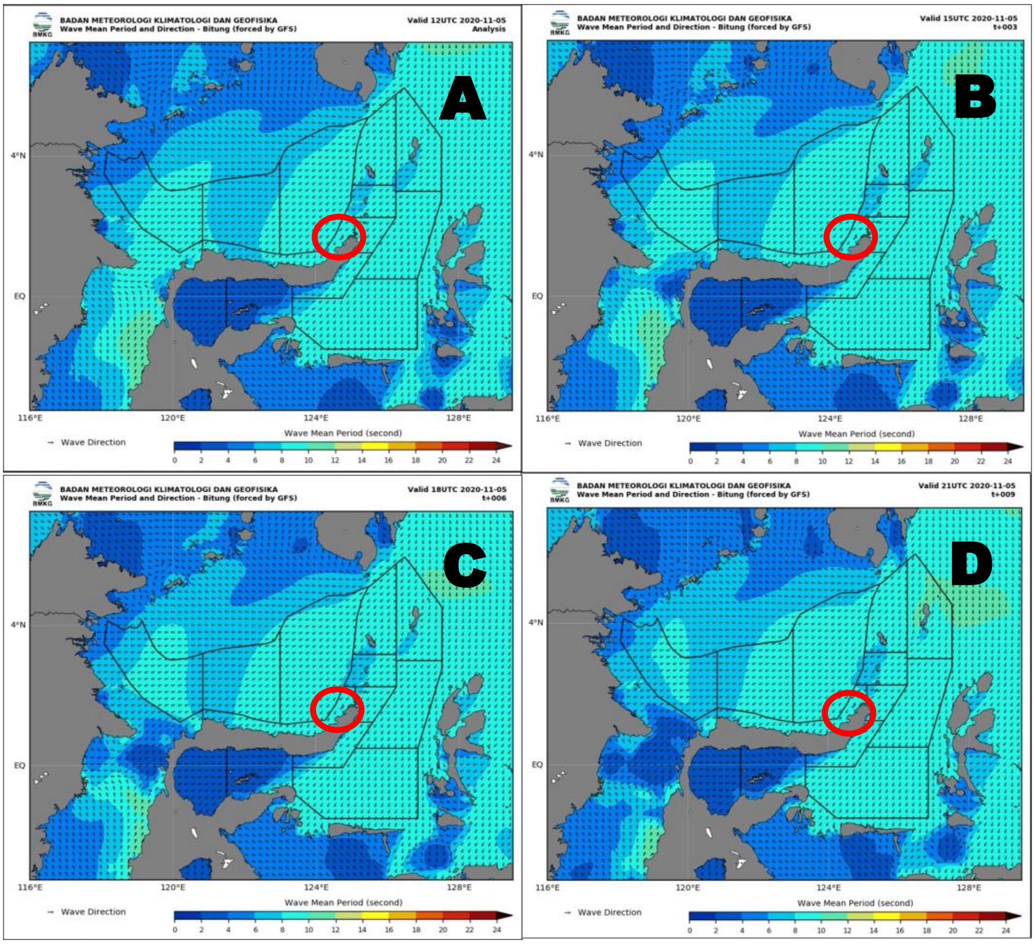
3b.1. Pemetaan Sumber Pencemar

Pengamatan terhadap keberadaan arus laut pada saat sebelum sampling dilakukan, yaitu pengamatan pada 5 November 2020 untuk sampling pada 6 November 2020 dan pengamatan 6 November 2020 untuk sampling pada 7 November 2020.

Gambar 3b.1 dan 3b.2 menampilkan citra Arah dan Periode Rerata Gelombang (*Wave Mean Periode and Direction*) pada 5 November 2020 dan 6 November (BMKG, 2020) di sekitar lokasi pengambilan sampel di perairan Teluk Manado. Dari citra tersebut nampak, periode rerata gelombang di sekitar lokasi pengambilan sampel berkisar 8-10 detik dengan arah gelombang (*wave direction*) ke arah Tenggara. Gambar 3b.3 dan 3b.4 menampilkan citra Kecepatan dan Arah Arus (*Current Speed and Direction*) pada 5 November 2020 dan 6 November 2020 (BMKG, 2020) di sekitar lokasi pengambilan sampel di perairan Teluk Manado. Nampak, kecepatan arus di sekitar lokasi pengambilan sampel berkisar 10-20 cm/detik di perairan dekat pantai, dengan arah arus ke Timur Laut, menyusuri pantai. Kecepatan arus 20-30 cm/detik juga terjadi di perairan jauh dari pantai.

Berdasarkan arah arus di Teluk Manado, keberadaan sampah laut di Pantai Malalayang diduga berasal dari daerah bagian Selatan. Di daerah pesisir daratan Teluk Manado bagian Selatan, umumnya merupakan daerah rural (pedesaan) dengan jumlah penduduk yang relatif sedikit. Namun, pada umumnya desa-desa tersebut berada di pinggiran pantai. Keberadaan sampah laut di Pantai Molas/Bailang diduga berasal dari sungai-sungai di bagian Selatan, yaitu 4 sungai besar yang melintasi Kota Manado dari dataran tinggi. Keempat sungai tersebut, yaitu S. Tondano, S. Malalayang, S. Sario, dan S. Bailang. Lokasi pengambilan sampel di Pantai Molas/Bailang berada bersebelahan dengan S. Bailang.

Keberadaan sampah pantai di Pantai Molas/Bailang merupakan *input* yang besar (*loading*) ke Teluk Manado dari Kota Manado dan daerah dataran tinggi di sekitarnya. Hal ini memberi dampak yang

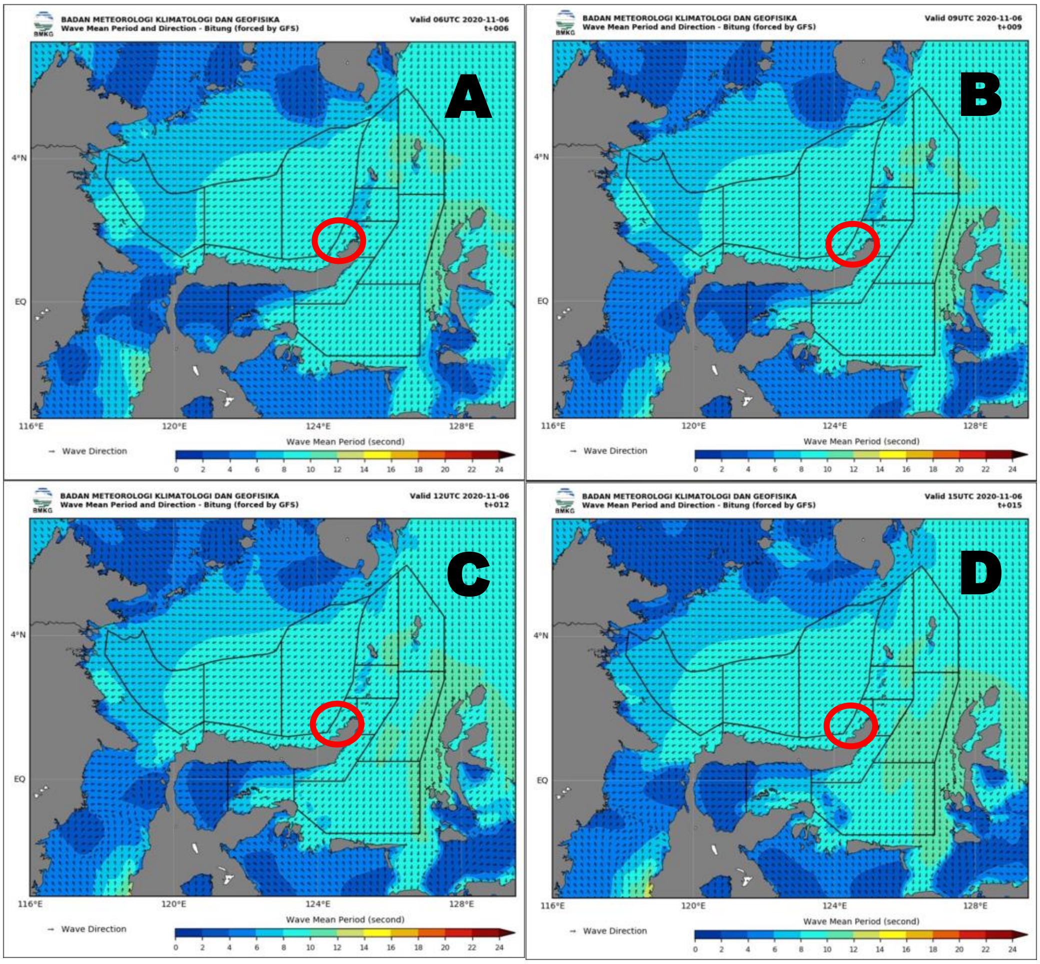


Gambar 3b.1. Periode Arah dan Periode Rerata Gelombang (*Wave Mean Periode and Direction*) di sekitar lokasi pengambilan sampel di Teluk Manado (BMKG, 2020) pada tanggal 5 November 2020.

(Keterangan: ○ Lokasi Pengambilan Sampel; A: Pukul 00.00; B: Pukul 03.00; C: Pukul 06.00; D: Pukul 09.00)

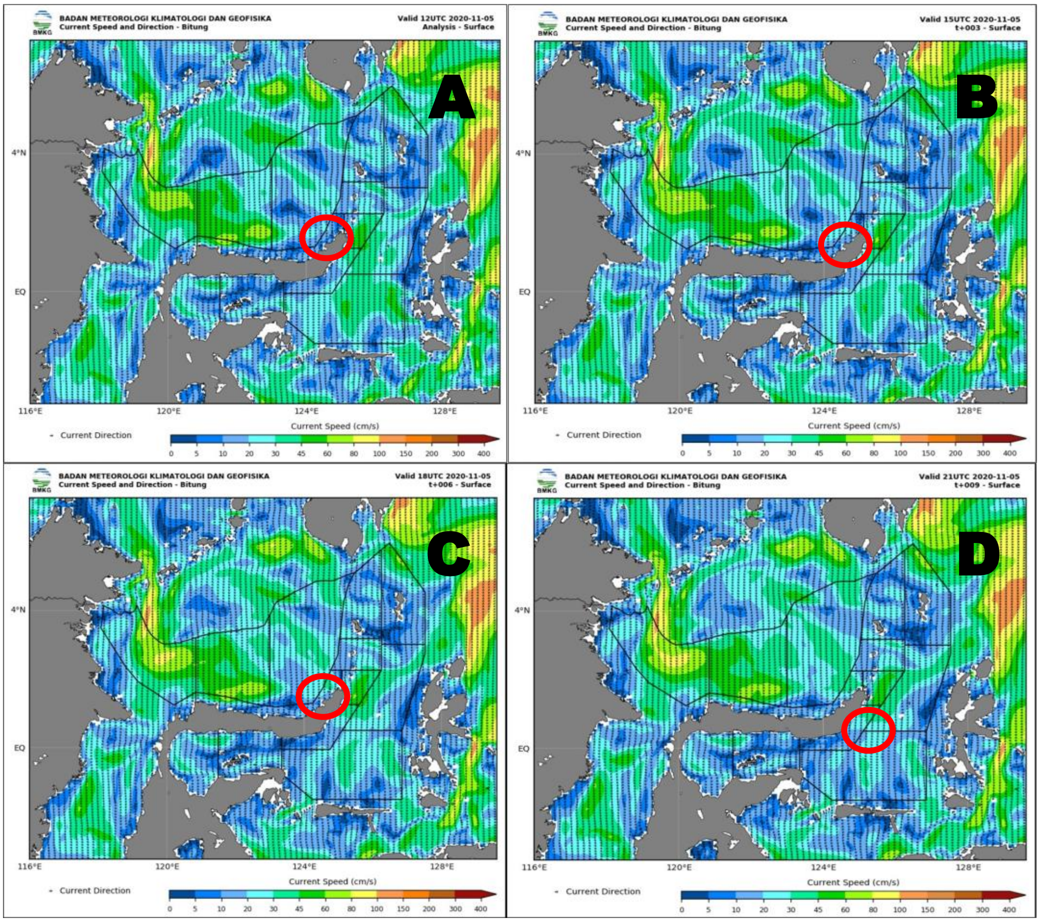
signifikan bagi keberadaan sampah laut di Teluk Manado, yang diduga dapat memberikan dampak lebih besar lagi ke Kawasan Taman Nasional Bunaken (TNB).

Secara umum, dinamika sampah laut, keradaan, dan vasiasinya, sangat erat kaitannya dengan banyak faktor, di antaranya, yaitu musim, arus dan gelombang laut, kecepatan dan arah arus, faktor oseanografi & meteorologi dan aktifitas perikanan (Krelling & Turra, 2019; Martin *et al.*, 2019; Pearce *et al.*, 2019; van Emmerik *et al.*, 2020; Zhang *et al.*, 2020).



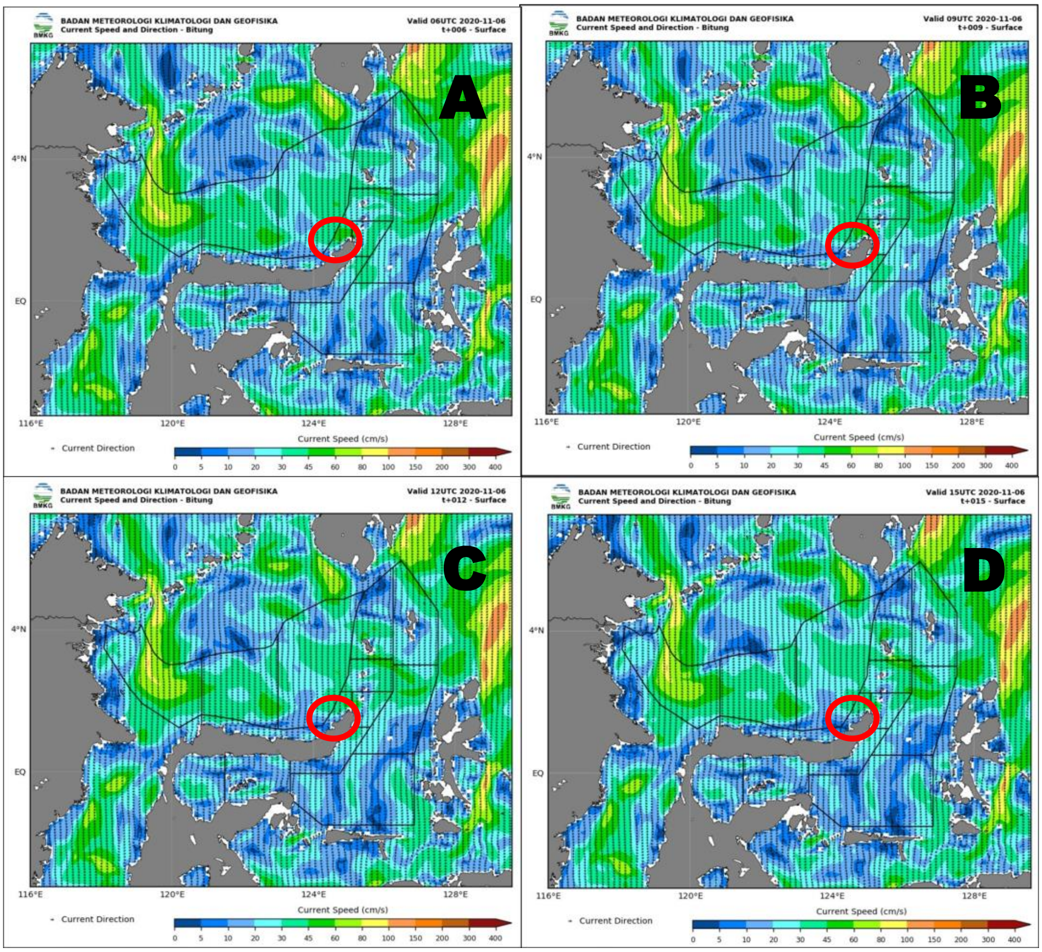
Gambar 3b.2. Periode Arah dan Periode Rerata Gelombang (*Wave Mean Periode and Direction*) di sekitar lokasi pengambilan sampel di Teluk Manado (BMKG, 2020) pada tanggal 6 November 2020.

(Keterangan: Lokasi Pengambilan Sampel; A: Pukul 06.00; B: Pukul 09.00; C: Pukul 12.00; D: Pukul 15.00)



Gambar 3b.3. Kecepatan dan Arah Arus (*Current Speed and Direction*) di sekitar lokasi pengambilan sampel di Teluk Manado (BMKG, 2020) pada tanggal 5 November 2020.

(Keterangan: Lokasi Pengambilan Sampel; A: Pukul 00.00; B: Pukul 03.00; C: Pukul 06.00; D: Pukul 09.00)



Gambar 3b.4. Kecepatan dan Arah Arus (*Current Speed and Direction*) di sekitar lokasi pengambilan sampel di Teluk Manado (BMKG, 2020) pada tanggal 6 November 2020.

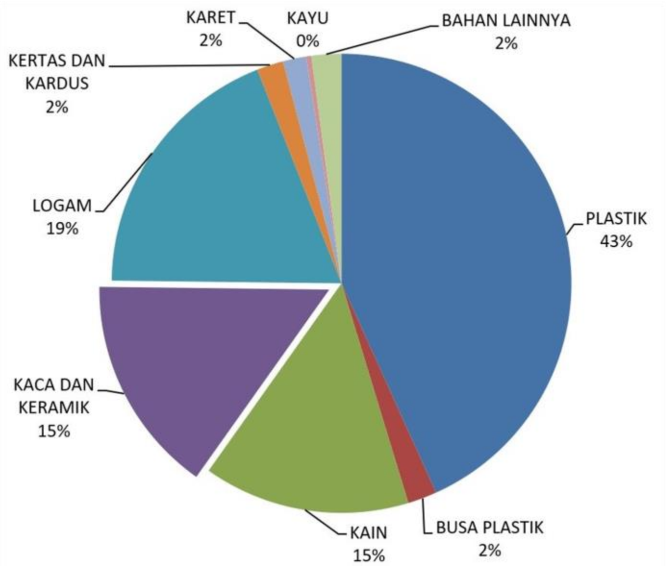
(Keterangan: Lokasi Pengambilan Sampel; A: Pukul 06.00; B: Pukul 09.00; C: Pukul 12.00; D: Pukul 15.00)

3b.2. Analisis Data dan Pembahasan

3b.2.1. Sampah Pantai Malalayang

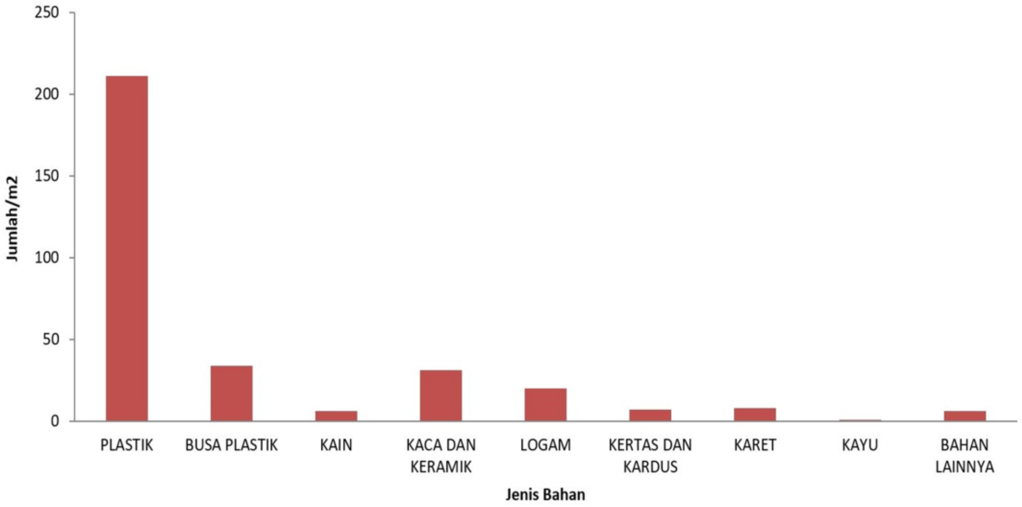
a. Sampah makro

Gambar 3b.5, Gbr. 3b.6, dan Gbr. 3b.7 menampilkan komposisi sampah pantai berukuran makro (> 2,5 cm) di Pantai Malalayang pada bulan November 2020, berturut-turut berdasarkan berat jenis bahan, jumlah jenis bahan, dan jumlah spesifikasi jenis. Nampak pada Gbr. 3b.5, berat tertinggi sampah pantai berukuran makro yaitu jenis plastik (43%), kemudian diikuti oleh jenis logam (19%). Sementara itu, jenis terbanyak berdasarkan jumlah yaitu jenis plastik dan diikuti oleh busa plastik (Gbr. 3b.6). Sedangkan berdasarkan jumlah spesifikasi jenis bahan, bahan plastik merupakan jenis yang terbanyak, khususnya wadah makanan (PL06) (Gbr. 3b.7).

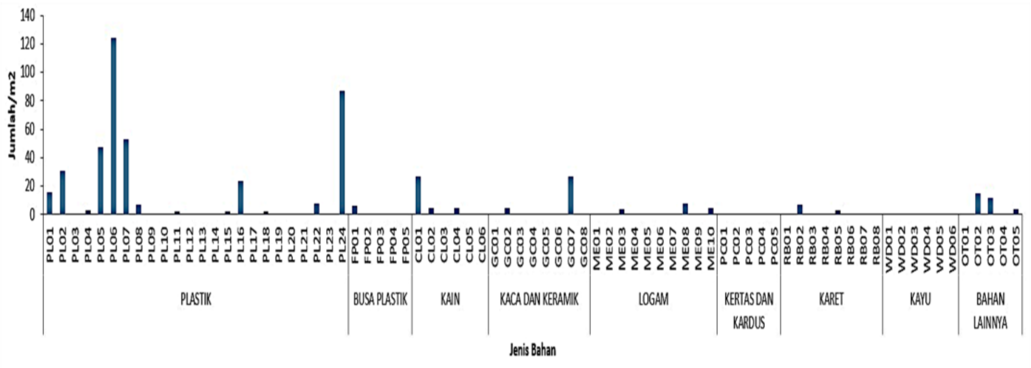


Gambar 3b.5. Komposisi sampah pantai berukuran makro (> 2,5 cm) berdasarkan berat jenis bahan di Pantai Malalayang, Kota Manado, pada bulan November 2020

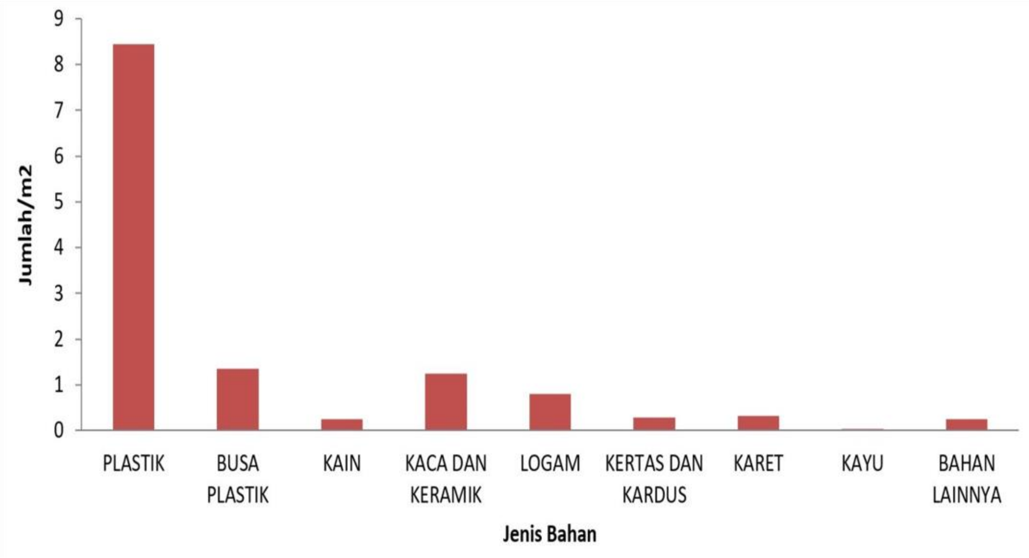
Gambar 3b.8 dan Gbr. 3b.9 menampilkan kepadatan sampah pantai berukuran makro di Pantai Malalayang, berturut-turut berdasarkan jenis bahan dan spesifikasi jenis bahan. Nampak, sampah pantai bahan plastik merupakan jenis yang terpadat (melebihi 8 potongan/m^2), dan diikuti oleh busa plastik (Gbr. 3b.8). Selain itu, spesifikasi jenis bahan yang tertinggi juga dari jenis plastik, khususnya wadah makanan (PL06). Demikian pula halnya jenis bahan plastik yang tertinggi yaitu wadah makanan (PL06) (Gbr. 3b.9).



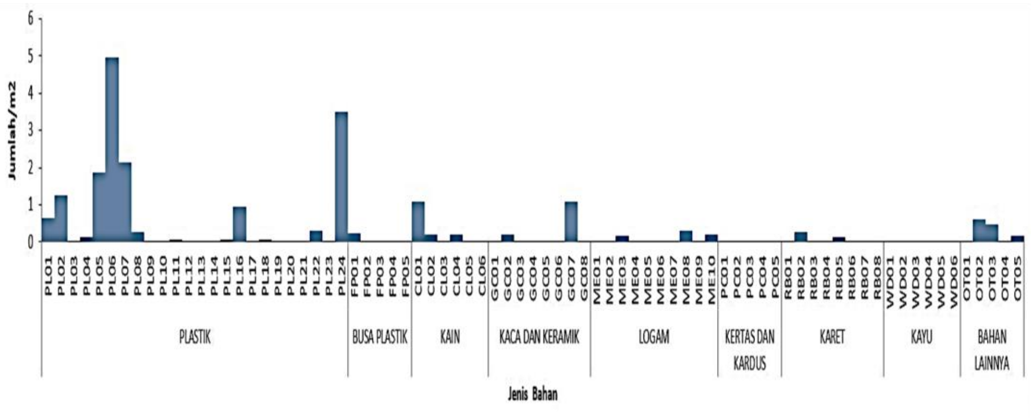
Gambar 3b.6. Komposisi sampah pantai berukuran makro (> 2,5 cm) berdasarkan jumlah jenis bahan di Pantai Malalayang, Kota Manado, pada bulan November 2020



Gambar 3b.7. Komposisi sampah pantai ukuran makro (> 2,5 cm) berdasarkan jumlah spesifikasi jenis bahan di Pantai Malalayang, Kota Manado, pada bulan November 2020



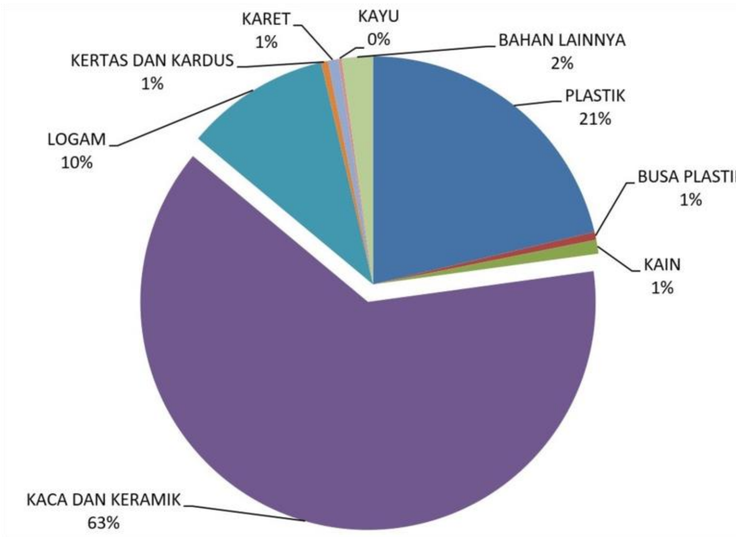
Gambar 3b.8. Kepadatan sampah pantai ukuran makro (> 2,5 cm) berdasarkan jenis bahan di Pantai Malalayang, Kota Manado, pada bulan November 2020



Gambar 3b.9. Kepadatan sampah pantai ukuran makro (> 2,5 cm) berdasarkan spesifikasi jenis bahan di Pantai Malalayang, Kota Manado, pada bulan November 2020

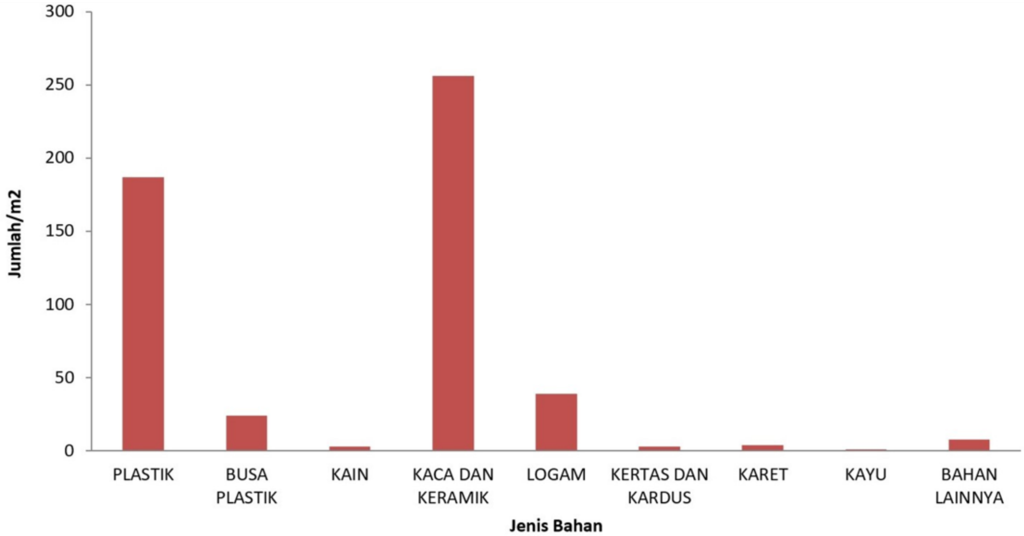
b. Sampah meso

Gambar 3b.10, Gbr. 3b.11, dan Gbr. 3b.12 menampilkan komposisi sampah pantai berukuran meso (5 mm-2,5 cm) di Pantai Malalayang pada bulan November 2020, berturut-turut berdasarkan berat jenis bahan, jumlah jenis bahan, dan jumlah spesifikasi jenis. Jenis bahan kaca dan keramik memiliki komposisi tertinggi (63%), yang diikuti oleh jenis bahan plastik (21%) (Gbr. 3b.10). Jenis bahan kaca dan keramik juga memiliki komposisi jumlah yang terbanyak (Gbr. 3b.11); namun, spesifikasi jenis yang terbanyak yaitu plastik, khususnya bahan plastik lainnya (Gbr. 3b.12).

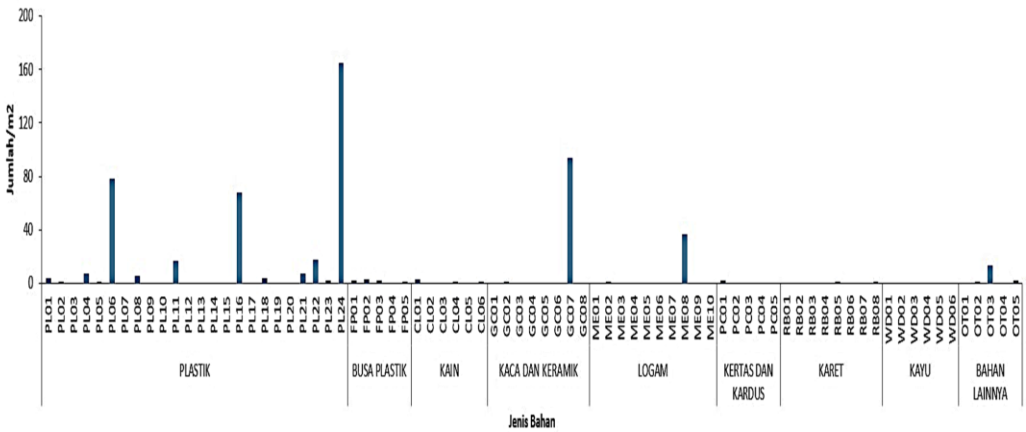


Gambar 3b.10. Komposisi sampah pantai berukuran meso (5 mm-2,5 cm) berdasarkan berat jenis bahan di Pantai Malalayang, Kota Manado, pada bulan November 2020

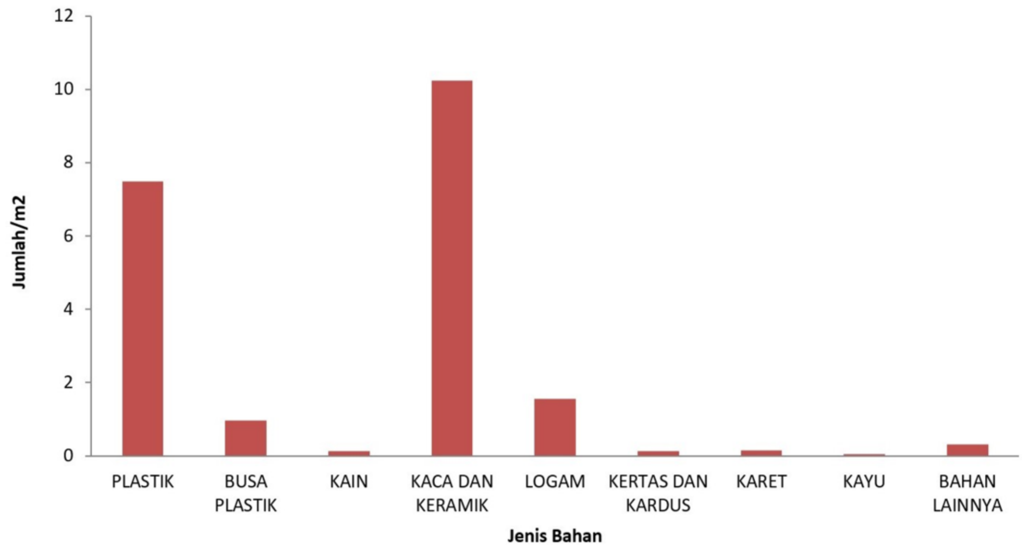
Gambar 3b.13 dan Gbr. 3b.14 menampilkan kepadatan sampah pantai berukuran meso di Pantai Malalayang, berturut-turut berdasarkan jenis bahan dan spesifikasi jenis bahan. Jenis bahan kaca dan keramik memiliki kepadatan yang tertinggi (Gbr. 3b.13), tetapi spesifikasi jenis bahan plastik, khususnya bahan plastik lainnya (PL24) yang terbanyak (Gbr. 3b.14).



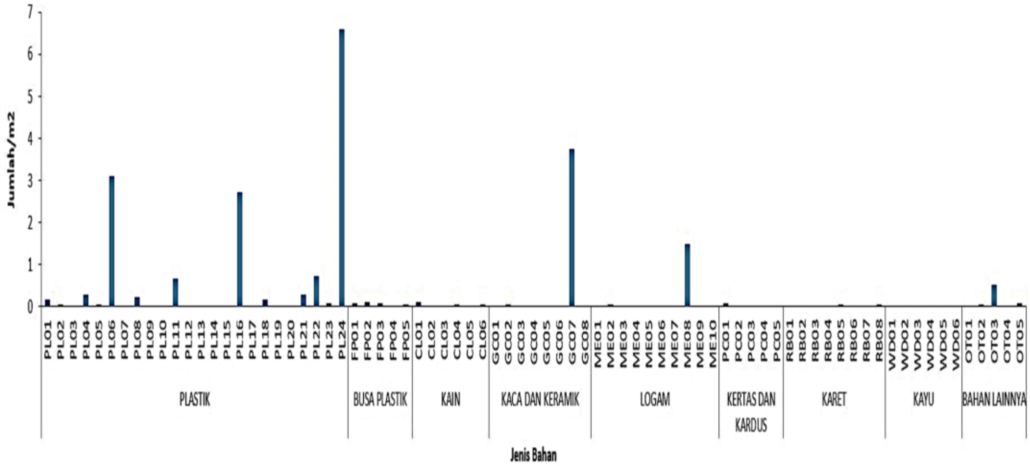
Gambar 3b.11. Komposisi sampah pantai berukuran meso (5 mm-2,5 cm) berdasarkan jumlah jenis bahan di Pantai Malalayang, Kota Manado, pada bulan November 2020



Gambar 3b.12. Komposisi sampah pantai ukuran meso (5 mm-2,5 cm) berdasarkan jumlah spesifikasi jenis bahan di Pantai Malalayang, Kota Manado, pada bulan November 2020



Gambar 3b.13. Kepadatan sampah pantai ukuran meso (5 mm-2,5 cm) berdasarkan jenis bahan di Pantai Malalayang, Kota Manado, pada bulan November 2020

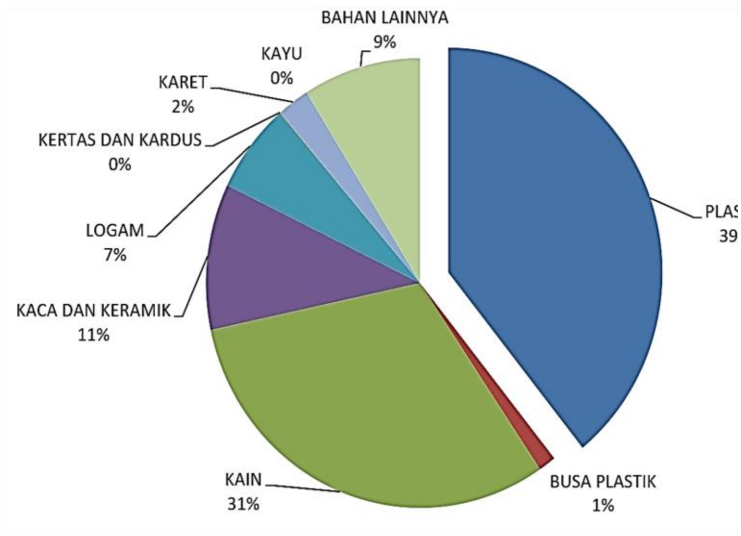


Gambar 3b.14. Kepadatan sampah pantai ukuran meso (5 mm-2,5 cm) berdasarkan spesifikasi jenis bahan di Pantai Malalayang, Kota Manado, pada bulan November 2020

3b.2.2. Sampah Pantai Molas/Bailang

a. Sampah makro

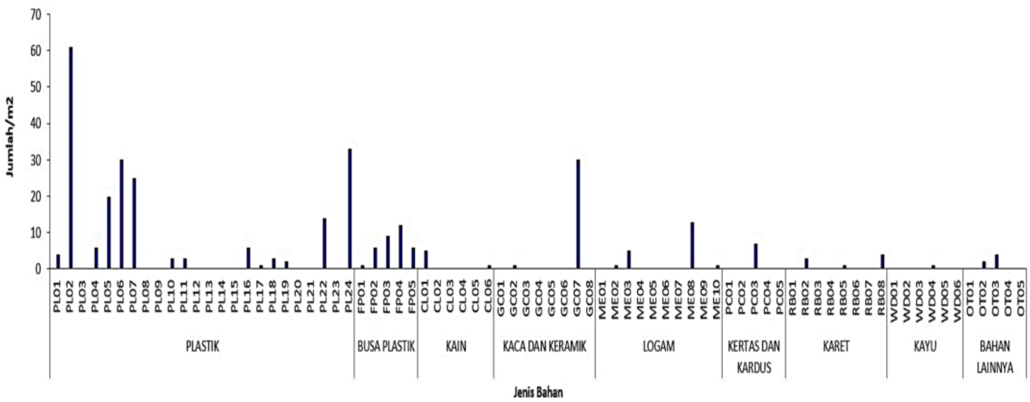
Gambar 3b.15, Gbr. 3b.16, dan Gbr. 3b.17 menampilkan komposisi sampah pantai berukuran makro (> 2,5 cm) di Pantai Molas/Bailang pada bulan November 2020, berturut-turut berdasarkan berat jenis bahan, jumlah jenis bahan, dan jumlah spesifikasi jenis. Tiga jenis bahan yang memiliki komposisi tertinggi, yaitu plastik (39%), kain (31%), dan kaca dan keramik (11%); di samping itu, bahan lainnya juga cukup tinggi (9%) (Gbr. 3b.15). Untuk komposisi berdasarkan jumlah, jenis bahan plastik merupakan yang tertinggi, dan diikuti oleh jenis kaca dan keramik, kain, serta bahan lainnya (Gbr. 3b.16). Komposisi sampah tertinggi berdasarkan spesikasi jenis bahan plastik, yaitu bahan plastik botol < 2 L (PL02) dan bahan plastik lainnya (PL24). Kemudian dari jenis bahan kaca dan keramik, yaitu pecahan kaca dan keramik (GC07) (Gbr. 3b.17).



Gambar 3b.15. Komposisi sampah pantai berukuran makro (> 2,5 cm) berdasarkan berat jenis bahan di Pantai Molas/Bailang, Kota Manado, pada bulan November 2020

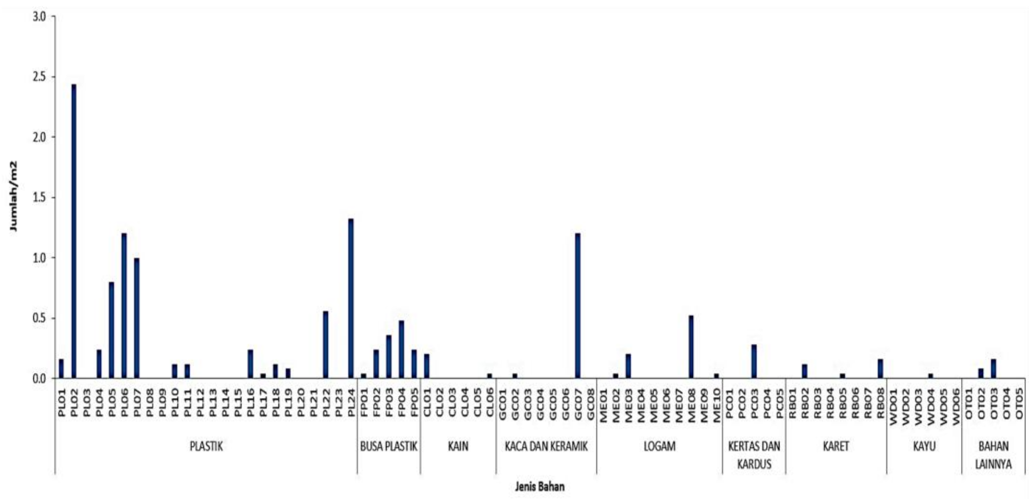
Gambar 3b.18 dan Gbr. 3b.19 menampilkan kepadatan sampah pantai berukuran makro di Pantai Molas/Bailang pada bulan November 2020, berturut-turut berdasarkan jenis dan spesifikasi bahan. Kepadatan sampah tertinggi didominasi oleh jenis bahan plastik (Gbr. 3b.18). Jenis bahan plastik tertinggi, yaitu spesifikasi bahan botol < 2 L (PL02) dan bahan plastik lainnya (PL24). Kepadatan jenis bahan plastik diikuti oleh jenis bahan kaca dan keramik, khususnya jenis pecahan kaca dan keramik (GC07) (Gbr. 3b.19).

Gambar 3b.16. Komposisi sampah pantai berukuran makro (> 2,5 cm) berdasarkan jumlah jenis bahan di Pantai Molas/Bailang, Kota Manado, pada bulan November 2020



Gambar 3b.17. Komposisi sampah pantai ukuran makro (> 2,5 cm) berdasarkan jumlah spesifikasi jenis bahan di Pantai Molas/Bailang, Kota Manado, pada bulan November 2020

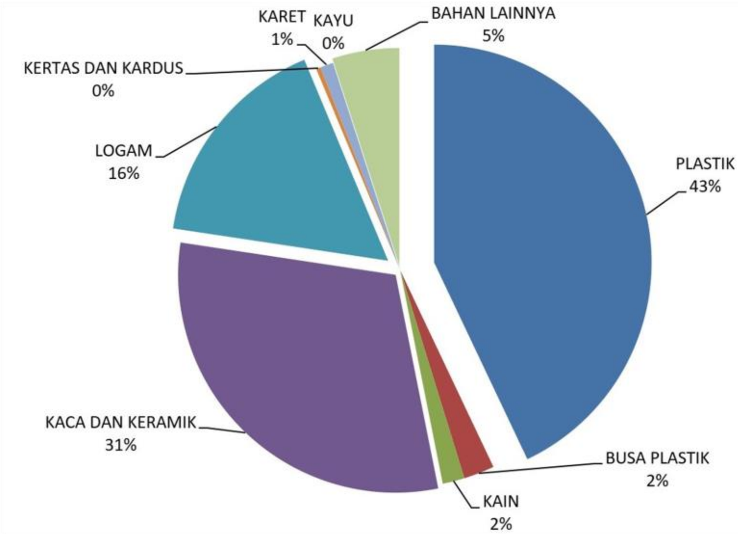
Gambar 3b.18. Kepadatan sampah pantai ukuran makro (>2,5 cm) berdasarkan jenis bahan di Pantai Molas/Bailang, Kota Manado, pada bulan November 2020



Gambar 3b.19. Kepadatan sampah pantai ukuran makro (> 2,5 cm) berdasarkan spesifikasi jenis bahan di Pantai Molas/Bailang, Kota Manado, pada bulan November 2020

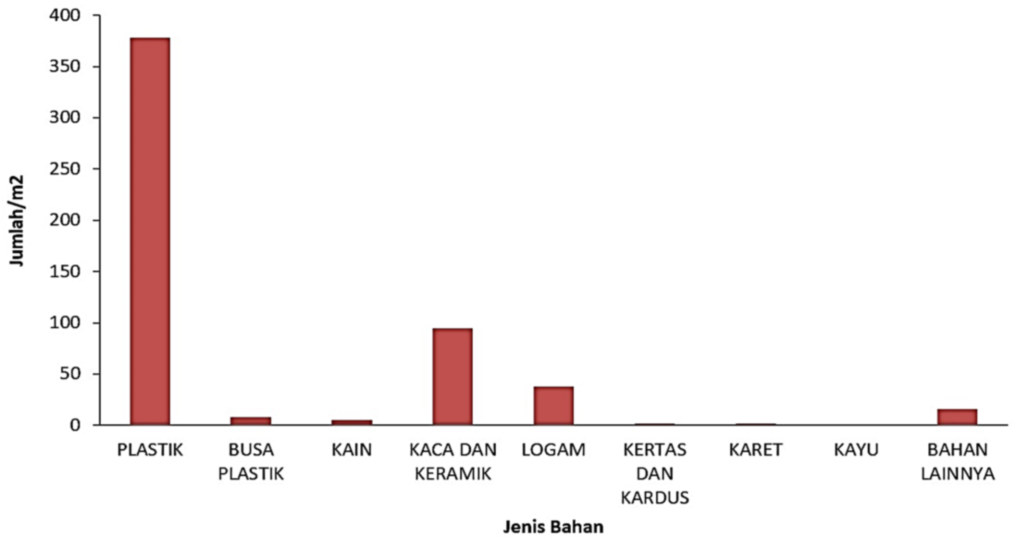
b. Sampah meso

Gambar 3b.20, Gbr. 3b.21, dan Gbr. 3b.22 menampilkan komposisi sampah pantai berukuran meso (5 mm-2,5 cm) di Pantai Molas/Bailang pada bulan November 2020, berturut-turut berdasarkan berat jenis bahan, jumlah jenis bahan, dan jumlah spesifikasi jenis. Nampak, 3 jenis bahan dengan komposisi tertinggi yaitu plastik (43%), kaca dan keramik (31%), dan logam (16%) (Gbr. 3b.20). Jumlah terbanyak juga didominasi, berturut-turut, oleh jenis bahan plastik, kaca dan keramik, dan logam (Gbr. 3b.21). Jumlah bahan tertinggi, berdasarkan spesifikasi, yaitu kaca dan keramik, khususnya jenis pecahan kaca dan keramik (GC07); untuk bahan plastik, yaitu jenis wadah makanan (PL06) dan bahan plastik lainnya (PL24); untuk bahan logam, yaitu serpihan logam (ME08) (Gbr. 3b.22).

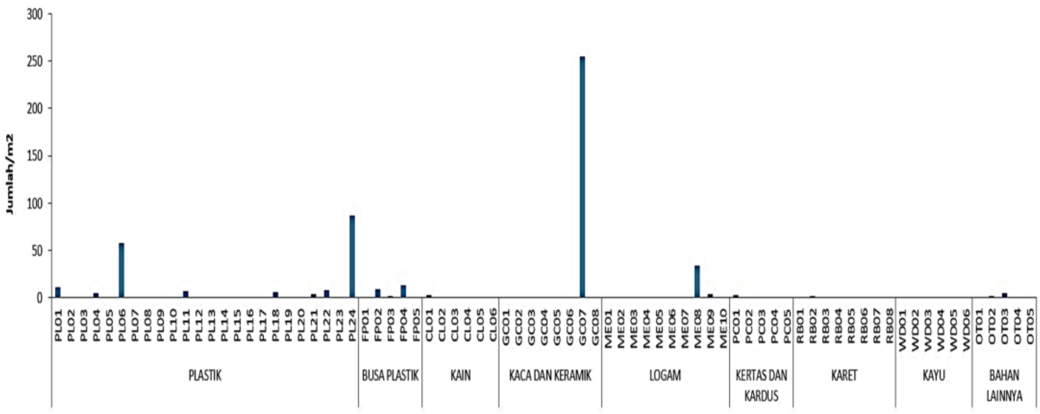


Gambar 3b.20. Komposisi sampah pantai berukuran meso (5 mm-2,5 cm) berdasarkan berat jenis bahan di Pantai Molas/Bailang, Kota Manado, pada bulan November 2020

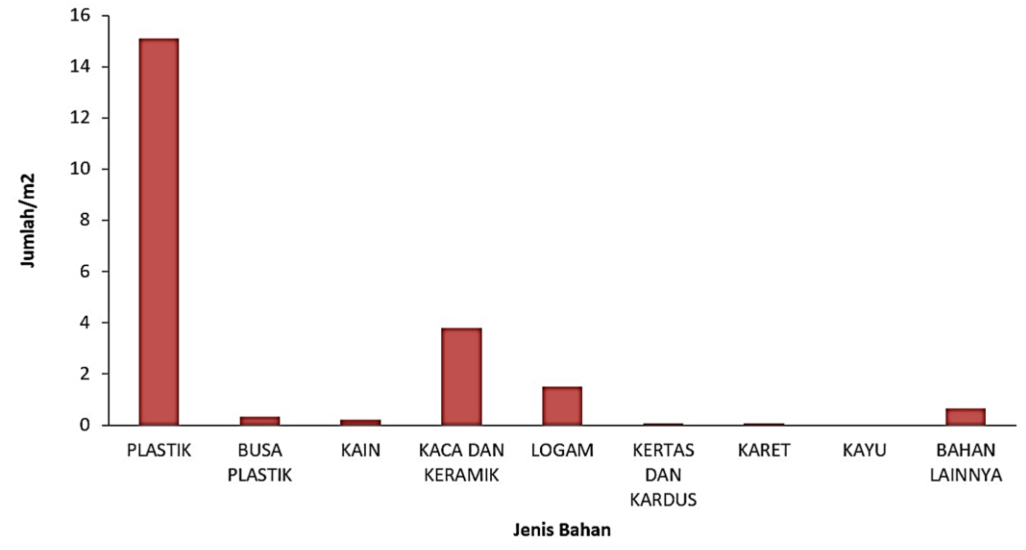
Gambar 3b.23 dan Gbr. 3b.24 menampilkan kepadatan sampah pantai berukuran meso di Pantai Molas/Bailang, berturut-turut berdasarkan jenis bahan dan spesifikasi jenis bahan. Sampah pantai terpadat yaitu jenis bahan plastik, kemudian diikuti oleh kaca dan keramik dan logam (Gbr. 3b.23). Spesifikasi bahan kaca dan keramik yang memiliki kepadatan tertinggi, yaitu pecahan kaca dan keramik (GC07). Sedangkan spesifikasi plastik yang memiliki kepadatan tertinggi yaitu jenis bahan plastik lainnya (PL24) dan wadah makanan (PL06) (Gbr. 3b.24).



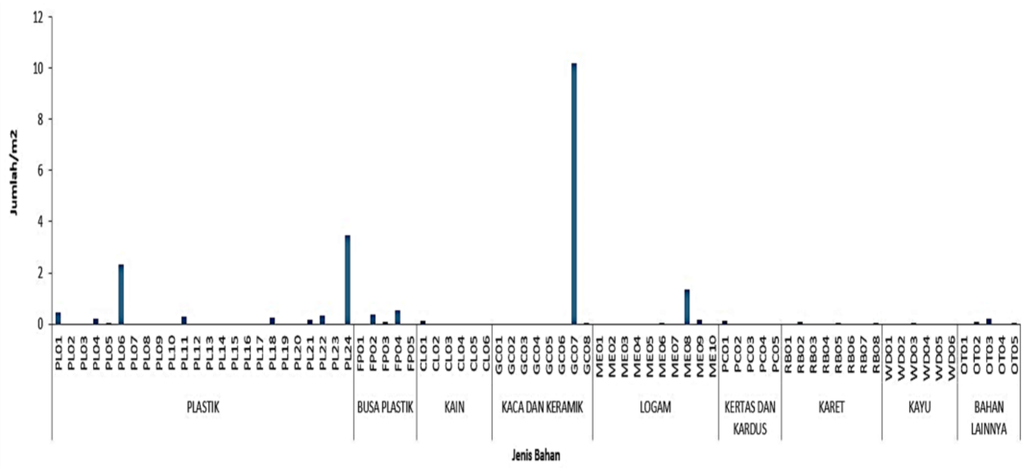
Gambar 3b.21. Komposisi sampah pantai berukuran meso (5 mm-2,5 cm) berdasarkan jumlah jenis bahan di Pantai Molas/Bailang, Kota Manado, pada bulan November 2020



Gambar 3b.22. Komposisi sampah pantai ukuran meso (5 mm-2,5 cm) berdasarkan jumlah spesifikasi jenis bahan di Pantai Molas/Bailang, Kota Manado, pada bulan November 2020



Gambar 3b.23. Kepadatan sampah pantai ukuran meso (5 mm-2,5 cm) berdasarkan jenis bahan di Pantai Molas/Bailang, Kota Manado, pada bulan November 2020



Gambar 3b.24. Kepadatan sampah pantai ukuran meso (5 mm-2,5 cm) berdasarkan spesifikasi jenis bahan di Pantai Molas/Bailang, Kota Manado, pada bulan November 2020

3b.2.3. Sampah Kota Manado

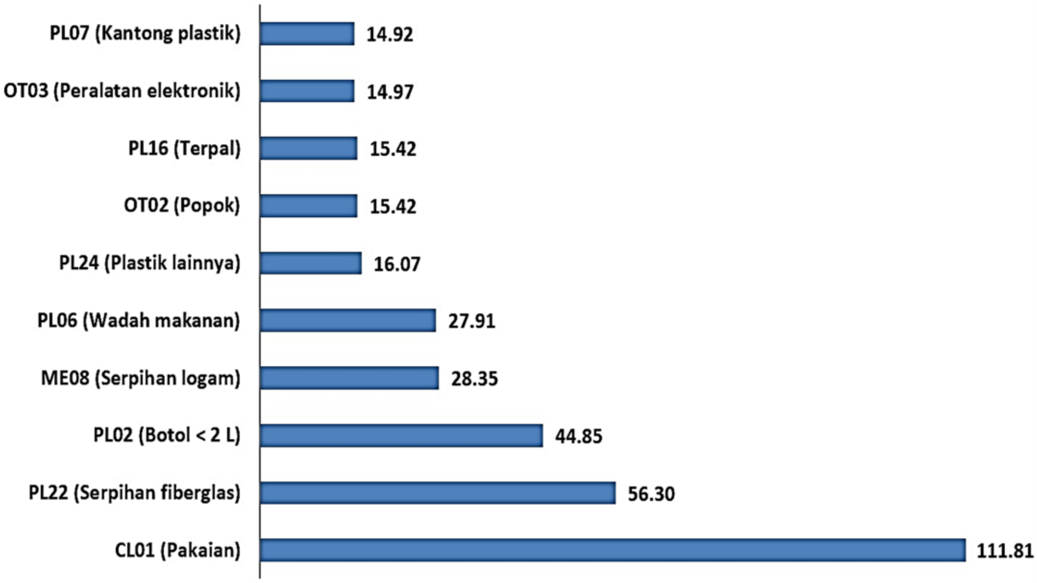
Tabel 3b.1 menampilkan range kepadatan (jumlah/m^2) sampah pantai di Kota Manado pada bulan November 2020, baik sampah berukuran makro maupun meso. Dari 9 jenis yang ditemukan, kepadatan sampah pantai tertinggi (16,28 potong/m^2 dan 15,12 potong/m^2) ditemukan pada jenis bahan plastik, berturut-turut berukuran makro dan meso.

Tabel 3b.1
Range kepadatan (jumlah/m^2) sampah pantai di Kota Manado pada bulan November 2020

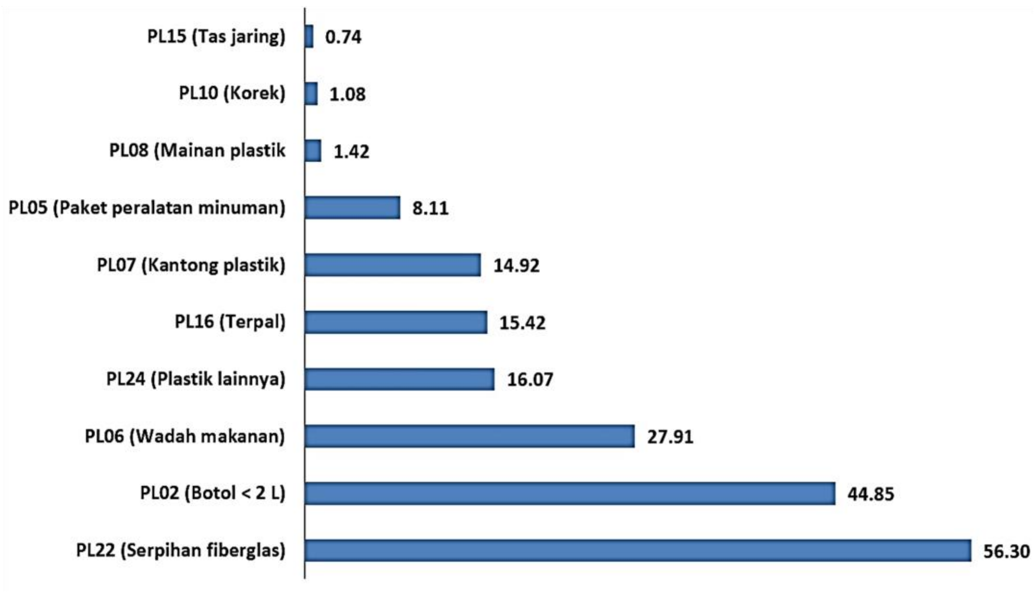
No	Jenis Sampah	Range Kepadatan (Jumlah/m^2)	
		Makro	Meso
1.	Plastik	8,44 - 16,28	7,48 - 15,12
2.	Busa Plastik	0,24 - 1,36	0,32 - 0,96
3.	Kain	0,24 - 1,48	0,12 - 0,20
4.	Kaca Dan Keramik	1,24 - 1,28	3,8 - 10,24
5.	Logam	0,68 - 0,80	1,52 - 1,56
6.	Kertas Dan Kardus	0,04 - 0,28	0,08 - 0,12
7.	Karet	0,32 - 0,40	0,08 - 0,16
8.	Kayu	0,00 - 0,04	0,00 - 0,04
9.	Bahan Lainnya	0,24 - 1,28	0,32 - 0,64

Gambar 3b.25 menampilkan 'Top 10' sampah pantai Kota Manado pada bulan November 2020 (gr/m^2). Jenis pakaian (CL01) merupakan sampah pantai tertinggi (111,81 gr/m^2); jenis bahan plastik, khususnya serpihan fiberglass (PL22) menempati urutan ke-2 (56,30 gr/m^2).

Khusus jenis bahan plastik, 'Top 10' sampah pantai dari jenis ini di Kota Manado pada bulan November 2020 (gr/m^2) ditampilkan pada Gbr. 3b.26. Nampak, serpihan fiberglass (PL22) memiliki jumlah (berat) tertinggi, yaitu sebesar 56,30 gr/m^2. Sedangkan, botol plastik < 2 L (PL02) berada pada urutan ke-2 dengan jumlah (berat) sebesar 44,85 gr/m^2.



Gambar 3b.25. Top 10 sampah pantai Kota Manado pada bulan November 2020 (gr/m^2)



Gambar 3b.26. Top 10 Sampah pantai dari jenis bahan plastik Kota Manado pada bulan November 2020 (gr/m^2)

4. KESIMPULAN

Hasil survei dapat disimpulkan sebagai berikut:

1. Sumber sampah pantai pada saat pengambilan sampel berasal dari daerah bagian Selatan Teluk Manado pada Tahap I (Agustus 2020) dan dari daerah bagian Utara teluk pada Tahap II (November 2020).
2. Pada Tahap I (Agustus 2020), sampah Pantai Malalayang berukuran makro, komposisi didominasi oleh jenis bahan kaca dan keramik; jumlah terbanyak adalah jenis bahan plastik; jumlah spesifikasi terbanyak adalah pecahan kaca dan keramik (GC07); kepadatan tertinggi didominasi oleh jenis bahan plastik; namun, kepadatan tertinggi berdasarkan spesifikasi jenis bahan adalah pecahan kaca dan keramik (GC07). Pada Tahap II (November 2020), Sampah Pantai Malalayang berukuran makro, komposisi didominasi oleh jenis bahan plastik; demikian pula untuk jumlah terbanyak ialah jenis bahan plastik; serta jumlah spesifikasi plastik terbanyak ialah wadah makanan (PL06); kepadatan tertinggi didominasi oleh jenis bahan plastik; demikian pula halnya kepadatan tertinggi berdasarkan spesifikasi jenis bahan ialah plastik jenis wadah makanan (PL06) dan jenis plastik lainnya (PL24).
3. Pada Tahap I (Agustus 2020), sampah Pantai Malalayang berukuran meso, komposisi tertinggi dan jumlah terbanyak didominasi oleh jenis bahan kaca dan keramik; jumlah spesifikasi terbanyak adalah pecahan kaca dan keramik (GC07); kepadatan tertinggi adalah jenis bahan kaca dan keramik; dan spesifikasi jenis yang memiliki kepadatan tertinggi adalah pecahan kaca dan keramik (GC07). Sedangkan pada Tahap II (November 2020), sampah Pantai Malalayang berukuran meso, komposisi tertinggi dan jumlah terbanyak didominasi oleh jenis bahan kaca dan keramik. Namun, jumlah spesifikasi terbanyak ialah plastik, khususnya dari jenus bahan plastik lainnya (PL24), kemudian diikuti oleh jenis pecahan kaca dan keramik (GC07). Kepadatan tertinggi adalah jenis bahan kaca dan keramik; namun, spesifikasi jenis yang memiliki kepadatan tertinggi ialah jenis bahan plastik lainnya (PL24).
4. Pada Tahap I (Agustus 2020), sampah Pantai Molas/Bailang berukuran makro, komposisi tertinggi dan jumlah terbanyak didominasi oleh jenis bahan plastik; jumlah spesifikasi terbanyak adalah bahan plastik lainnya (PL24); kepadatan tertinggi adalah jenis

bahan plastik; dan spesifikasi jenis yang memiliki kepadatan tertinggi adalah bahan plastik lainnya (PL24). Sedangkan pada Tahap II (November 2020), sampah Pantai Molas/Bailang berukuran makro, komposisi tertinggi dan jumlah terbanyak didominasi oleh jenis bahan plastik; dan jumlah spesifikasi terbanyak adalah bahan botol plastik < 2 L (PL02). Kepadatan tertinggi adalah jenis bahan plastik; dan spesifikasi jenis yang memiliki kepadatan tertinggi adalah jenis botol plastik < 2 L (PL02).

5. Pada Tahap I (Agustus 2020), sampah Pantai Molas Bailang berukuran meso, komposisi tertinggi dan jumlah terbanyak didominasi oleh jenis bahan plastik; jumlah spesifikasi terbanyak adalah bahan plastik lainnya (PL24); demikian pula halnya untuk kepadatan tertinggi adalah jenis bahan plastik; dan spesifikasi jenis yang memiliki kepadatan tertinggi adalah bahan plastik lainnya (PL24). Sedangkan pada Tahap II (November 2020), sampah Pantai Molas Bailang berukuran meso, komposisi tertinggi dan jumlah terbanyak didominasi oleh jenis bahan plastik; namun, jumlah spesifikasi terbanyak ialah jenis pecahan kaca & keramik (GC07); demikian pula halnya untuk kepadatan tertinggi adalah jenis bahan plastik; dan spesifikasi jenis yang memiliki kepadatan tertinggi ialah jenis pecahan kaca & keramik (GC07).
6. Sembilan jenis bahan ditemukan sebagai sampah pantai di Kota Manado dengan kepadatan tertinggi dari jenis bahan plastik, baik berukuran makro maupun meso.
7. Jenis bahan pakaian (CL01) merupakan sampah pantai tertinggi dari 'Top 10' jenis sampah yang ditemukan; dan spesifikasi plastik terpal (PL16) merupakan jenis bahan plastik yang menjadi sampah pantai tertinggi dari 'Top 10' bahan plastik pada Tahap I (Agustus 2020), dan serpihan fiberglass (PL22) pada Tahap II (November 2020).

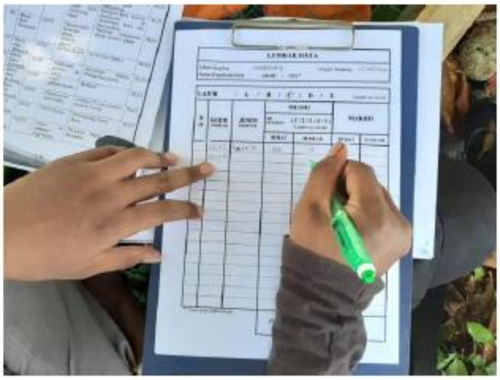
Survei pengambilan sampel di Pantai Malalayang
(pelaksanaan survei tanggal 17 Agustus 2020)

Keberadaan transek dan sub transek

Proses pengumpulan sampel makro

Proses pengumpulan sampel meso

Proses penimbangan sampel



Proses pencatatan dan klasifikasi

Pembersihan lokasi setelah sampling

Survei pengambilan sampel di Pantai Molas/Bailang
(pelaksanaan survei tanggal 18 Agustus 2020)

Keberadaan transek (sisi Selatan)

Keberadaan transek (sisi Utara)

Proses pengumpulan sampel meso

Proses pengumpulan sampel makro

Sampah pantai ukuran besar (log kayu)

Sampah pantai ukuran besar (sponge)

Survei pengambilan sampel di Pantai Malalayang
(pelaksanaan survei tanggal 7 November 2020)

Keberadaan transek dan sub transek

Proses pengumpulan sampel makro

Proses pengumpulan sampel meso

Proses penimbangan sampel

Proses pencatatan dan klasifikasi

Pembersihan lokasi setelah sampling

Survei pengambilan sampel di Pantai Molas/Bailang
(pelaksanaan survei tanggal 6 November 2020)


Keberadaan transek di lapangan


Cara pembuatan sub sub transek


Proses pengumpulan sampel meso


Proses pengumpulan sampel makro


Pengumpulan sampah pantai


Pengumpulan sampah pantai

Informasi Pantai Molas/Bailang

Informasi Pantai [Formulir PL.02]	Pelaksana Survei	Pascasarjana UNSRAT	
	N. Telp./E-mail	085298070889 / lasut.markus@unsrat.ac.id	
	Tanggal Survei	18 Agustus 2020	
Informasi Umum			
Nama Pantai	Pantai Molas / Bailang		
Alamat	Jalan Bailang Raya		
Desa/Kelurahan	Molas		
Kecamatan	Bunaken		
Kabupaten	Kota Manado		
Provinsi	Sulawesi Utara		
Koordinat Pantai	Lat: 1.524727°	Long: 124.842616°	
Karakteristik Pantai			
Panjang area pantai	± 150 m		
Lebar pantai	± 37.6 m		
Slope garis pantai	82.3° – 84.1°		
Tipe pantai (*berpasir, berbatu, dll.*)	Pasir dan berkarang pada bagian tertentu		
Mayoritas tipe dasar (%) *(persentase pasir dan batu/kerikil/karang)*	Pasir: 90% Karang: 10%		
Batas pantai *(bangunan, vegetasi, tebing, dll.)*	Vegetasi		
Jarak pasang surut maksimum dan minimum (meter) diukur dari batas pantai	± 385 m		
Arah pantai *(pilih salah satu)*	[ ] Utara	[ ] Timur Laut	
	[ ] Timur	[ ] Tenggara	
	[X] Barat	[ ] Barat Daya	
	[ ] Selatan	[ ] Barat Laut	

Informasi Pantai Malalayang

Informasi Pantai [Formulir PL.02]	Pelaksana Survei	Pascasarjana UNSRAT
	N. Telp./E-mail	085298070889 / lasut.markus@unsrat.ac.id
	Tanggal Survei	17 Agustus 2020
Informasi Umum		
Nama Pantai	Pantai Malalayang	
Alamat	Jalan Wolter Monginsidi	
Desa/Kelurahan	Malalayang Satu Barat	
Kecamatan	Malalayang	
Kabupaten	Kota Manado	
Provinsi	Sulawesi Utara	
Koordinat Pantai	Lat: 1.460207°	Long: 124.804088°
Karakteristik Pantai		
Panjang area pantai	± 200 m	
Lebar pantai	± 20 m	
Slope garis pantai	84.3° – 85.3°	
Tipe pantai (*berpasir, berbatu, dll.*)	Pasir campur kerikil	
Mayoritas tipe dasar (%) *(persentase pasir dan batu/kerikil/karang)*	Kerikil: 70% Pasir: 30%	
Batas pantai *(bangunan, vegetasi, tebing, dll.)*	Batas memanjang: vegetasi dan bangunan Batas lebar: vegetasi	
Jarak pasang surut maksimum dan minimum (meter) diukur dari batas pantai	Minimum: ± 50 m Maksimum: ± 100 m	
Arah pantai *(pilih salah satu)*	[X] Utara [ ] Timur [ ] Barat [ ] Selatan	[ ] Timur Laut [ ] Tenggara [ ] Barat Daya [ ] Barat Laut

Informasi Sumber Sampah di Pantai Molas Bailang

Informasi Pantai [Formulir PL.02]	Pelaksana Survei	Pascasarjana UNSRAT		
	N. Telp./E-mail	085298070889 / lasut.markus@unsrat.ac.id		
	Tanggal Survei	6 November 2020		
Informasi Umum				
Nama Pantai	Pantai Molas / Bailang			
Alamat	Jalan Bailang Raya			
Desa/Kelurahan	Molas			
Kecamatan	Bunaken			
Kabupaten	Kota Manado			
Provinsi	Sulawesi Utara			
Koordinat Pantai	Lat:	1.524727°	Long:	124.842616°
Karakteristik Pantai				
Panjang area pantai	± 150 m			
Lebar pantai	± 37.6 m			
Slope garis pantai	82.3° – 84.1°			
Tipe pantai (*berpasir, berbatu, dll.*)	Pasir dan berkarang pada bagian tertentu			
Mayoritas tipe dasar (%) *(persentase pasir dan batu/kerikil/karang)*	Pasir: 90% Karang: 10%			
Batas pantai *(bangunan, vegetasi, tebing, dll.)*	Vegetasi			
Jarak pasang surut maksimum dan minimum (meter) diukur dari batas pantai	± 385 m			
Arah pantai *(pilih salah satu)*	[ ]	Utara	[ ]	Timur Laut
	[ ]	Timur	[ ]	Tenggara
	[X]	Barat	[ ]	Barat Daya
	[ ]	Selatan	[ ]	Barat Laut

Informasi Sumber Sampah di Pantai Malalayang

Informasi Pantai [Formulir PL.02]	Pelaksana Survei	Pascasarjana UNSRAT
	N. Telp./E-mail	085298070889 / lasut.markus@unsrat.ac.id
	Tanggal Survei	7 November 2020
Informasi Umum		
Nama Pantai	Pantai Malalayang	
Alamat	Jalan Wolter Monginsidi	
Desa/Kelurahan	Malalayang Satu Barat	
Kecamatan	Malalayang	
Kabupaten	Kota Manado	
Provinsi	Sulawesi Utara	
Koordinat Pantai	Lat: 1.460207°	Long: 124.804088°
Karakteristik Pantai		
Panjang area pantai	± 200 m	
Lebar pantai	± 20 m	
Slope garis pantai	84.3° – 85.3°	
Tipe pantai (*berpasir, berbatu, dll.*)	Pasir campur kerikil	
Mayoritas tipe dasar (%) *(persentase pasir dan batu/kerikil/karang)*	Kerikil: 70% Pasir: 30%	
Batas pantai *(bangunan, vegetasi, tebing, dll.)*	Batas memanjang: vegetasi dan bangunan Batas lebar: vegetasi	
Jarak pasang surut maksimum dan minimum (meter) diukur dari batas pantai	Minimum: ± 50 m Maksimum: ± 100 m	
Arah pantai *(pilih salah satu)*	[X] Utara [ ] Timur [ ] Barat [ ] Selatan	[ ] Timur Laut [ ] Tenggara [ ] Barat Daya [ ] Barat Laut

LAMPIRAN

Artikel Publikasi Ilmiah tentang Sampah Laut
di mana Penulis Terlibat sebagai Penulis Utama
dan Penulis Pendamping (*co-author*)

DAFTAR ISI

Seasonal variation of marine debris at Manado Bay (North Sulawesi, Indonesia)

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Abstract. Marine debris has become a global concern due to its impact on marine ecosystems. These materials generally come from land and are deposited to marine environment through different agent of carrier. Many efforts are being made to monitor the dynamics of the debris including their presence and their variability in relation to seasons. The latter are assumed from the facts that the presence of the debris is mainly affected by the waves, speed, and direction of ocean currents in the area of interest. In this study, variation of debris in dry and wet season at Manado Bay was assessed by using a shoreline technique. Two locations are selected, Bailang and Malalayang beach. The samplings were conducted in August 2019 (represent dry season) and January 2020 (represent wet season). Several parameters are examined during the sampling; they are: amount of material, type of debris, composition, and spatial density of each type for macro-size (>2.5 cm) and meso-size (0.5–2.5 cm). The results showed that there was variation on composition and density, but the types of debris remain unchanged. Our present study concluded that variation in the season do not affect the variability of marine debris in Manado Bay.

Keywords: Bunaken; Indonesia; marine debris; plastic; seasonal variation

1. Introduction

Waste has become a global problem nowadays. It can be found everywhere and has a huge impact on the environment both on land and in the ocean [1–5]. Marine debris is found in or near the ocean and are originated from land which are resulted from human activities. They enter marine environment through rivers, drainage channels, and are also carried by visitors of a beach [6–9], and their fate is influenced by waste management activities on land [2, 5]. Most of marine debris is very harmful to the marine resources, ecosystem, economy and social life [1, 10].

In 2016, Indonesia became the country with the world largest mismanaged plastic waste [4.3 million metric ton (Mt)] from the total of 9.1 Mt waste production [11]. It has increased from 3.22 Mt in 2010

[12]. In order to prevent it to worsen, Indonesian government has issued a regulation in 2018 through a Presidential Decree Number 83 which governs Marine Debris Management. The regulation aims to establish strategies, program and activities in the form of a national action plan in handling marine debris from 2018 to 2025. One of the activities implemented is monitoring, which includes monitoring marine debris in Manado Bay. The Bay is located in northern part of Sulawesi Island, Indonesia. The area of the bay is very strategic because it is in the middle area of world coral triangle and has the Bunaken National Park as the outer part [5] and also an area of an important traditional fishing for the locals.

Bunaken National Park, one of the three Unesco's biosphere reserves in Indonesia, which is known for its coral reefs [5] faces a threat of marine debris which could be brought by current from Manado Bay, originated from Manado city. In January to April 2018, garbage removed from Bunaken Island (one of five islands in Bunaken National Park) weighed up to 3 tons [13]. Meanwhile, according to Central Bureau of Statistics [14] the number of domestic and foreign visitors in Manado has reached 1,739,729 people. This expected to be a threat to Manado Bay and Bunaken National Park which the quantity of garbage can increase and will have a negative impact on the residence, and in particular to the marine environment [5], in addition to other impacts cause by liquid waste [15].

One of the efforts in monitoring marine debris in Manado Bay is by accessing their presence and dynamics in the sea. In general, the dynamic of marine debris, its existence and variation, are closely related to seasons, tides, wave, current speed and direction, oceanography and meteorology factors and fishing activities [16–20]. The monitoring is very important to reduce ecological threat that could possibly occur [3, 21].

The study aimed to assess the variation of marine debris in Manado Bay in two ranges of sizes, macro (>2.5 cm) and meso (0.5–2.5 cm), based on different seasons (dry and wet) by using different parameter (type, amount, composition, density) and shoreline technique (assessment of shoreline segments). The study was an integral part of the research conducted by Pane *et al.* [22] and is part of marine debris monitoring program in Manado Bay waters and around Bunaken National Park funded by the Ministry of Environment and Forestry of the Republic of Indonesia.

2. Material and methods

2.1. Study site

The observation was conducted in Manado Bay, North Sulawesi, Indonesia. Two locations were selected as sampling sites. The first location is Malayang Beach, geographically located at 1°27'36,0" N and 124°48'15.0" E. The beach is located at the southern part of the bay and is facing north. The substrates consist of sands with gravel, and beach faces north, sandy beach mixed with gravel, and slope range 82.3 to 84.1°, and is bordered by vegetation to the land. The second location is Bailang Beach, located in 01°31'32.0" N and 124°50'32.0" E. It lies on the northern part of the bay and faces west. It has a muddy substrate type and slope range of 82.3° to 84.1°, bordered by vegetation to the land (figure 1).

Manado Bay is open sea water facing west toward Sulawesi Sea, which is on the western side of northern part of Sulawesi Island. Part of northern side of the bay is included in Bunaken National Park area which is known for its high biodiversity and is diving site [5]. Based on its position, Manado Bay forms a water-front city toward Manado city. Malalayang Beach (around 5 kms from the city center) is a peri-urban area and also a tourism area; it is allocated for fishing and access to the sea. The source of debris generally comes from the sea, and they are stranded by current and waves. Bailang Beach (around 4 km from the city center) is an urban area of Manado city and is not intended for tourism, so there is only for fishing and also access to the sea. The presence of debris in this area is basically from the sea and also Bailang River which is situated next to the sampling site.

The selection of the location was done by following the Guidelines for Monitoring Coastal Waste published by the Ministry of Environment and Forestry of Republic of Indonesia [23] which adopted the guidelines of Cheshire *et al.* [24] and Lippiatt *et al.* [10]. The guidelines require, among other things, that location should be accessible throughout the year or season (for continuous monitoring), sandy or gravel substrates, there are no breakwaters, jetties, docks or other structures, has a gentle to moderate slope, there is no clean-up activities around the area during sampling, and there is nowaste management facilities at the location. Since 2017, both beaches have been designated to be permanent observation locations for marine debris monitoring in Manado Bay [25].

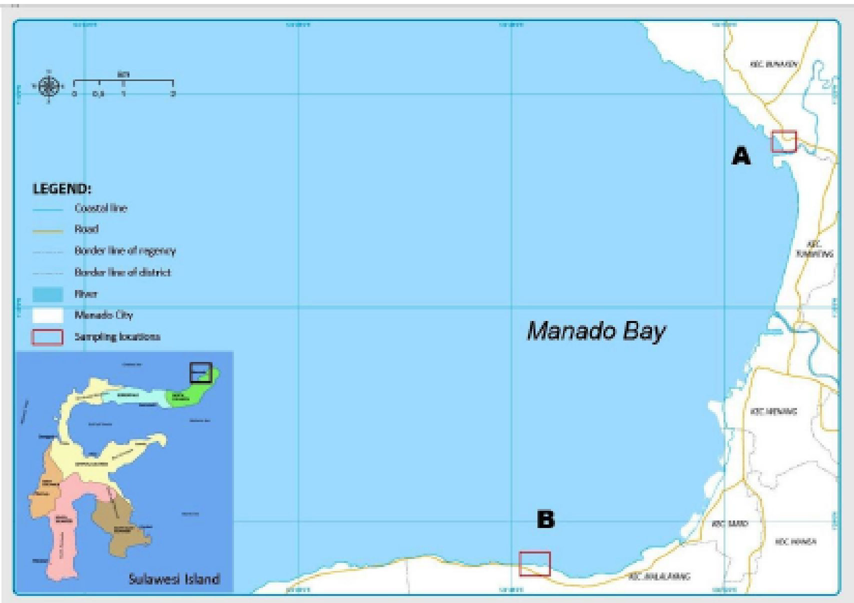

Figure 1. Study location in Manado Bay. A: Bailang Beach (BB), B: Malalayang Beach (MB).

2.2. Sampling time and technique

The marine debris sampling was carried out once in each season, on July 19th and 20th 2019 for dry season and on January 24th and 25th 2020 for wet season. The differences between those two seasons are based on the average monthly precipitation which reached 17.66 cm in July and 33.11 cm in January. Debris sampling in both seasons was carried out at the same location and with similar sampling procedure.

Sampling was conducted by using the guidelines of marine debris quantification published by Ministry of Environment and Forestry of the Republic of Indonesia [23] which has been used nationally in Indonesia since 2017. This method was adapted for the condition in Indonesian waters from the method issued by NOAA [10]. Observation was made during low tide using shoreline technique on macro- (>2.5 cm) and meso-debris (0.5–2.5 cm) waste materials. Sampling area on the coast was defined at the length of 100 m parallel to the coastline; the first line was established at the nearest part of the water; and it was 20 m wide. Sampling area was divided into 5 lanes (perpendicular to the coastline), each 20 m apart. A quadrate (5 m^2, 2 replicates) was placed on each lane. This 5 m^2 quadrates was then divided into 25 small quadrates (1 m^2), and 5 of these sub-quadrates were randomly selected and were further divided into 4 small parts (0.25 m^2). These 4 parts were then labeled as section A, B, C and D. Section A is on upper left side facing the sea and the other parts (B, C, and D) were on the clockwise direction.

Sampling of the marine debris was done at 5 subquadrates (which has been divided into section A to D) in each lane. At section A, the surface of the sand was peeled off to the depth of 5-10 cm and all the substrates was collected (together with marine debris) by using a scoop. All the sands in Section A were collected into 2 sieves at the same time. The 0.5 cm steel sieve (made of steel) was at the bottom to collect the meso-size debris and the 2.5 cm steel sieve was on the top to collect the macro-debris. All the collected debris that has been passed through 0.5 cm sieve was then put into plastic bags and labeled. The debris which was collected from 2.5 cm sieve was put into a plastic bag. Section B to C were also peeled to the depth of 5 to 10 cm, collected using a scoop, and put together with all the collected debris in Section A and labeled.

All the sampling bags were stored properly. They were classified, calculated, and weighed. The classification was carried using the guidelines from UNEP/IOC Guidelines on Survey and Monitoring of Marine Debris [24]. They were then weighed with a scale (to the accuracy of 0.1 g) and counted based on the type of materials. All the data were recorded in the datasheet.

2.3. Data analysis
The data obtained during the sampling was calculated based on the guidelines provided by Ministry of Environment and Forestry of Indonesia [23], by determining their composition and density of the debris material. The composition was calculated from the weight percentage of the debris for each type in total waste. Meanwhile, the density was calculated from the percentage of waste (fragment) per type in m^2. The calculation for each size was performed differently. Statistical tests were applied, among others Kolmogorov-Smirnov test to find out the distribution of the data, Wilcoxon Signed Rank test was performed to find out the differences between season toward data that are not normally distributed, and paired T test for normally distributed data.

3. Results and discussions

3.1. Types of marine debris
Marine debris was found in Manado Bay, at both study sites, in both dry and wet seasons and both sizes. The debris consists of 9 types of materials, there are plastics (PL), glass and ceramic (GC), foamed plastic (FP), paper and cardboard (PC), metal (ME), cloth (CL), rubber (RB), wood (WD), and other (OT). There was only a slight variation occurred in the number of types based on season for both sizes.

The number of debris items for macro size in Malalayang Beach for dry and wet season were 25 and 24, respectively; while in Bailang Beach 33 and 32. The meso-size in Malalayang Beach for dry and wet season were 17 and 17, and for Bailang Beach were 24 and 22.

Marine debris found during the study was classified according to UNEP/IOC Guidelines on Survey and Monitoring of Marine Debris [24]. They were plastic materials, glass and ceramic materials, foamed plastic, metal, rubber materials, cloth materials and others. The plastic materials include bottle caps & lids (PL01), bottles < 2 L (PL02), jerrycans (PL03), straws (PL04), drink package rings (PL05), food containers (PL06), plastic bags (PL07), cigarettes butts & filters (PL11), monofilament line (PL18), strapping (PL21), fiberglass fragments (PL22), and other plastics (PL24). Glass & ceramic materials include construction materials (GC01), bottles (GC02), cups (GC03), and glass fragments (GC07). Foam packing (styrofoam) (FP04) was classified into foamed plastic. Paper & cardboard materials were cups and drink containers (PC03), and other paper & cardboards (PC05). Those which are made of metal were bottle caps (ME02), aluminum drink cans (ME03), metal fragments (ME08), wire (ME09), and other metals (ME10). Rubber materials include tires (RB04), inner-tubes (RB05), and other rubbers (RB08). Matches (WD05) and other woods (WD06) were classified into wood materials. From cloth material is other cloth (CL06); and those include in other materials were sanitary (tampon) (OT02), electronics equipment (OT03), and other (OT05).

3.2. Composition of marine debris
The highest composition of macro-size debris found in dry season was the plastic materials; it covers 33%, while glass and ceramic material (50%) dominated the wet season (figure 2). Glass and ceramic

dominated the meso-size debris in dry and wet seasons with the composition of 56% and 72%, respectively (figure 3).

The average of total weight of macro-size marine debris in Manado Bay in dry and wet season during the study was 8,217.93 g and 9.551.32 g, respectively. One of the materials that was different in composition was glass and ceramic; this material was only 17% of all materials during dry season but increased to 50% in wet season. Several materials decreased in composition; plastic was, among others. This type of material had a composition of 33% in dry season and decreased to 23% in wet season. One other material, rubber, was 7% in dry season, decreased to 0%. This showed a variation of macro-size marine debris, but the variation was found to be non-significant ($p > 0.05$).

The composition of meso-size marine debris in Manado in dry and wet seasons was also different. The average of total weight of this size was 338.65 g in dry season and 344.10 g in wet season. One of the materials that increased from dry to wet season was glass and ceramic, the composition in dry season was 56% and increased to 72% in wet season. It was differed from plastic materials which decreased from 34% in dry season to 21% in wet season. But then the difference in composition was found to be non-significant ($p > 0.05$).

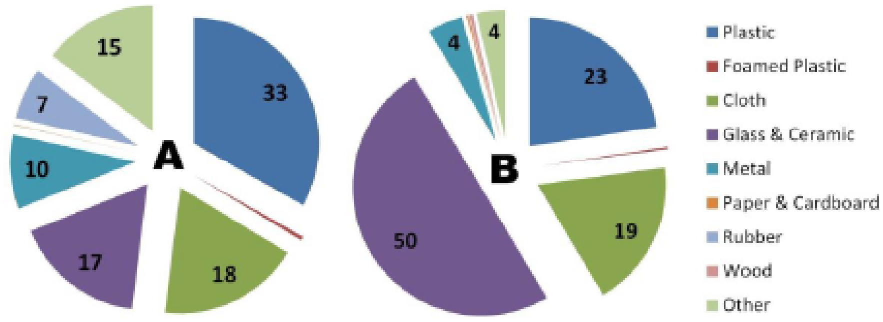

Figure 2. Percent composition of marine debris for macro-size debris (>2,5 cm) in Manado Bay, North Sulawesi, Indonesia (A: dry season; B: wet season).

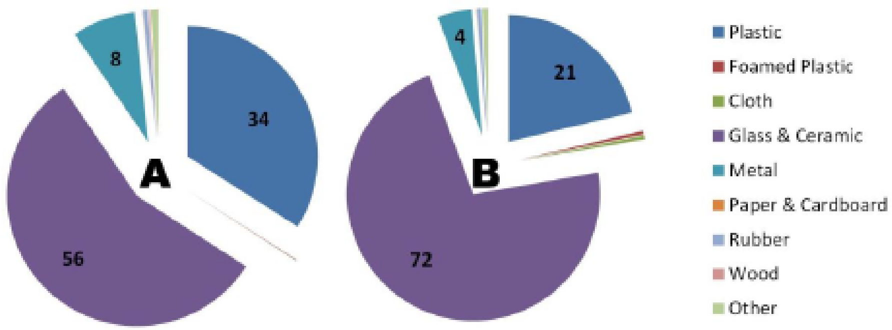

Figure 3. Percent composition (%) of marine debris for meso-size debris (0.5–2.5 cm) in Manado Bay, North Sulawesi, Indonesia (A: dry season; B: wet season).

The same condition was reported by Djaguna *et al*. [26] and Bangun *et al*. [27] that marine debris of the plastic material was the most dominant type of materials in beaches around Manado Bay. They found that more than 50% of the marine debris found in Tongkaina Beach, Talawaan Bajo Beach, Tasik Ria Beach and Tumpaan Beach was categorized as plastic materials. This is in line with Jambeck *et al*. [12] who reported that Indonesia is one of the largest contributors of plastic waste to the marine environment in the world.

3.3. Density of marine debris

Density of marine debris both macro and meso-sizes in Manado Bay in dry and wet season was also determined (figure 4 and figure 5). For macro-size debris, it was found that plastic material was the dominant one in both on dry and wet seasons. The density of this material was found to be 6.25 fragment/m² and 9.18 fragment/m², respectively. It was then followed by glass and ceramic which has the density of 1.64 fragment/m² and 1.95 fragment/m²). Foamed plastic has a higher density in wet season (0.53 fragment/m²) than dry season (0.10 fragment/m²). For meso-size (figure 5), the highest density in dry season was plastic materials (11.04 fragment/m²), and it was followed by glass and ceramic (7.7 fragment/m²), metal (0.98 fragment/m²). The same highest density for plastic material was also found in wet season (12.86 fragment/m²) and followed by glass and ceramic (10.04 fragment/m²). Foamed plastic was a little bit higher in wet season (0.80 fragment/m²) than in dry season (0.16 fragment/m²).

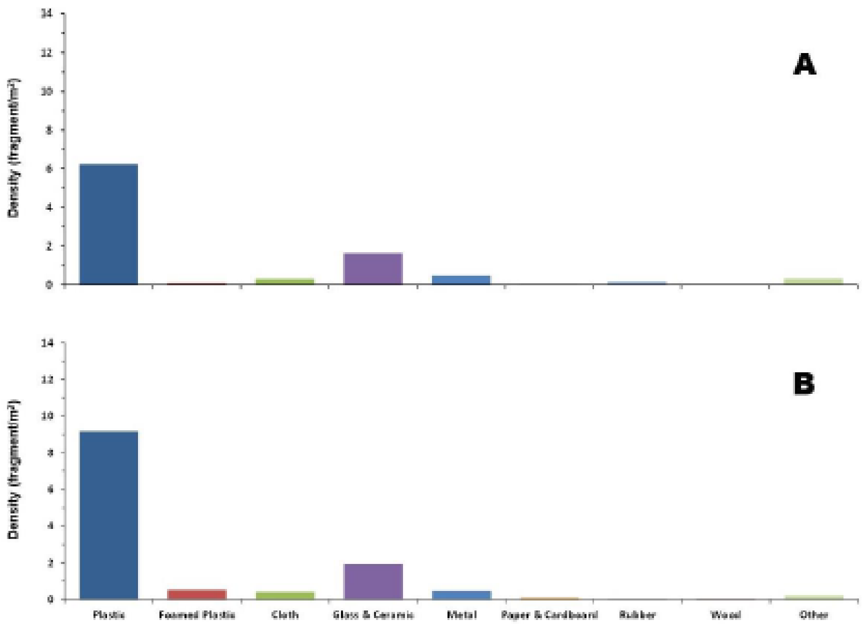

Figure 4. Density (fragment/m²) of marine debris for macro-size debris (>2.5 cm) in Manado Bay, North Sulawesi, Indonesia (A: dry season; B: wet season).

When comparing the study in dry and wet season of marine debris in Manado Bay, the wet season has a slightly higher density of marine debris than the dry season, both in macro and meso-size. In dry season, the average of total density of macro size marine debris was 9.34 fragment/m² and it increased to 12.92 fragment/m² in wet season. The same goes to meso-size, the average of total density in dry season was 20.34 fragment/m² and it increased to 24.78 fragment/m² in wet season; the was a 4.44 fragment/m² differences. However, this was not significantly difference ($p > 0.05$). The similar finding was reported by Bangun *et al.* [27] in Tasik Ria Beach. This area is approximately 12 km to the south of Malalayang Beach and is also part of Manado Bay.

The abundance of marine debris is influenced by season [21], rainfall, winds and tides [4, 17, 19, 28, 29, 30], input from rivers to the sea also plays a significant role in contributing the increase of the debris materials [19, 30–32], and high population of coastal communities, for instance in Indonesia [33]. During wet season, as the river water discharge increases, more waste from the land would accumulate in coastal area around the river mouth. This probably the case in Manado Bay, especially in Bailang Beach where the plastic materials dominated the wet season because of the increasing of water discharge from the river. However, tourism activities in the beach during dry season can also increase the abundance of marine debris [29].

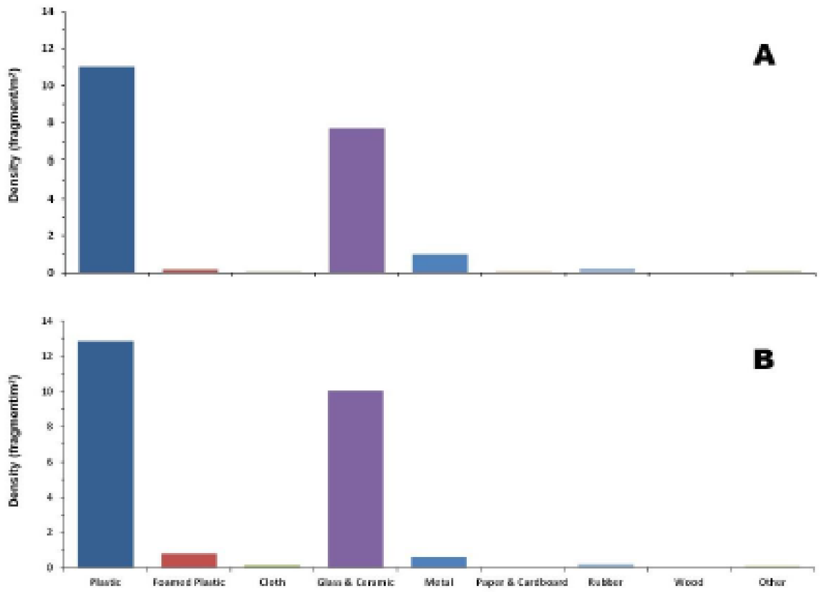

Figure 5. Density (fragment/m²) of marine debris for meso debris (0.5–2.5 cm) in Manado Bay, North Sulawesi, Indonesia (A: dry season; B: wet season).

According to Thiel *et al.* [29], the accumulation of marine debris in beach varies in different types of beach. For the rocky type beach, the debris that arrives on the beach can be crushed by the waves and currents in the shore area. This is probably the case in Malalayang Beach which has the rocky type beach, in which the meso-size materials were dominated by glass and ceramic. The accumulation of marine debris was also influenced by the river input [19–20]; this could be the case in Bailang Beach where the debris arrive from the land through Bailang River.

4. Conclusions

Based on study on marine debris in Manado Bay it was concluded that there was no variation of the marine debris found in the area. However, further study is needed to find out the factors that can affect the presence of marine debris in the area and how they behave during dry and wet season.

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Half-Life of Biodegradable Plastics in the Marine Environment Depends on Material, Habitat, and Climate Zone

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The performance of the biodegradable plastic materials polyhydroxybutyrate (PHB), polybutylene sebacate (PBSe) and polybutylene sebacate co-terephthalate (PBSeT), and of polyethylene (LDPE) was assessed under marine environmental conditions in a three-tier approach. Biodegradation lab tests (20°C) were complemented by mesocosm tests (20°C) with natural sand and seawater and by field tests in the warm-temperate Mediterranean Sea (12–30°C) and in tropical Southeast Asia (29°C) in three typical coastal scenarios. Plastic film samples were exposed in the eulittoral beach, the pelagic open water and the benthic seafloor and their disintegration monitored over time. We used statistical modeling to predict the half-life for each of the materials under the different environmental conditions to render the experimental results numerically comparable across all experimental conditions applied. The biodegradation performance of the materials differed by orders of magnitude depending on climate, habitat and material and revealed the impreciseness to generically term a material "marine biodegradable." The half-life $t_{0.5}$ of a film of PHB with 85 μm thickness ranged from 54 days on the seafloor in SE Asia to 1,247 days in mesocosm pelagic tests. $t_{0.5}$ for PBSe (25 μm) ranged from 99 days in benthic SE Asia to 2,614 days in mesocosm benthic tests, and for PBSeT $t_{0.5}$ ranged from 147 days in the mesocosm eulittoral to 797 days in Mediterranean benthic field tests. For LDPE no biodegradation could be observed. These data can now be used to estimate the persistence of plastic objects should they end up in the marine environments considered here and will help to inform the life cycle (impact) assessment of plastics in the open environment.

Keywords: Mediterranean Sea, Southeast Asia, surface erosion rate, environmental persistence, lifecycle assessment, polybutylene sebacate, polybutylene sebacate co-terephthalate, polyhydroxybutyrate

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INTRODUCTION

Global plastic production is growing exponentially. It has almost doubled since the beginning of this century (European Bioplastics, 2020) to 400 Mt in 2020 (including fibers) and is estimated to reach 800 Mt in 2050 (Rouch, 2019). Biodegradable polymers are a small, but growing segment in this market with a share of 0.3 % (1.227 Mt) in 2020 (European Bioplastics, 2020). The amount of plastic entering the natural environment is augmenting rapidly, accumulating at an exponential rate (Geyer et al., 2017). If introduced to the environment, e.g., as litter, it can be assumed that most items made from biodegradable plastic materials have similar pathways and sinks as conventional non-biodegradable plastic items. Plastic pollution is found almost anywhere in nature it has been looked for, including air (e.g., Dris et al., 2016), high-mountain and polar ice (e.g., Ambrosini et al., 2019; Kanhai et al., 2020), terrestrial soil (e.g., review by Helmberger et al., 2019), freshwater (e.g., Wagner et al., 2014) and marine systems (e.g., Weber et al., 2015; Figure 2 and references therein) with effects on ecosystem level, organism level and on humans still to be fully understood.

Biodegradable plastics are used as alternative materials to conventional plastics, e.g., for agricultural films (e.g., Sintim and Flury, 2017) and/or as substitutes required by legislation such as fruit and vegetable bags (Journal Officiel de la République Française, 2016; Gazzetta Ufficiale della Repubblica Italiana, 2017). Biodegradable polymers are discussed as a mitigation strategy against environmental plastic pollution (Republic of Indonesia, 2017). The European Commission in their European Plastics Strategy (European Commission, 2018) stated that new plastics with biodegradable properties bring new opportunities but also risks. It was also pointed out the importance to make sure that biodegradable plastics are not put forward as a solution to littering.

For some applications where the unintentional loss of plastic to the environment is intrinsic to its use (e.g., fishing gear, boating gear, and beach tourism items) or which are prone to unavoidable input (e.g., abrasion of tires, shoes, textiles, paint) and thus are continuously introduced to the environment, biodegradable polymeric alternatives might be the only solution from the material side (Albertsson et al., 2020).

There is no universal definition, yet several descriptions and definitions of the term "biodegradation" exist, which might lead to decision-making based on wrong assumptions and even to misuse, false claims, and disinformation. Following the biogeochemical point of view, we define "biodegradation" of a carbon-based polymer as the mineralization to carbon dioxide (and in the absence of oxygen also methane), water, and the incorporation of its breakdown products into new biomass by naturally occurring bacteria, archaea, and fungi, leaving no residue behind.

Hence, "biodegradability" describes the capacity of a polymeric material to be broken down by microorganisms in the considered receiving environment. As the abundance, diversity, and activity of microorganisms vary in nature as do the environmental conditions, also the specific biodegradation at a given place and time will vary. To be truly meaningful, the term "biodegradable" must therefore be clarified and linked not only to a duration in time, compatible with a human scale but also to the conditions under which biodegradation occurs, and to be seen as a system property (Albertsson et al., 2020).

As reliable, comparable, and verifiable information is needed and officially asked for (The European Green Deal, European Commission, 2019) the claim "biodegradable" of a certain material should be sufficiently specified and reliably proven. Therefore suitable tests are needed (Harrison et al., 2018).

Here, we tested the performance of biodegradable plastic in the marine environment applying laboratory methods proposed by Tosin et al. (2012) and field and mesocosm methods developed during the EU project Open-Bio (Lott et al., 2016a,b, 2020). In a 3-tier approach, we answered the questions whether the tested materials are biodegradable at all, whether biodegradation does take place under real natural marine conditions, and at which rates in the different environmental settings.

To enable a numerical comparison of the experimental results we applied a statistical model to the experimental results to mathematically describe the biodegradation over time with a specific half-life. This number can further be used as a material property specific for defined environmental conditions and used to set thresholds, estimate environmental risk, and be fed into lifecycle assessment.

In this study, we tested three biodegradable polymers with natural marine seawater and sediments in lab and mesocosm tests, and in field tests in three coastal marine scenarios in the Mediterranean Sea and in tropical Southeast Asia. We focused on three easily accessible habitats in coastal shallow water: the intertidal beach, the open water, and the sandy seafloor.

MATERIALS AND METHODS

Test Materials

Four polymer materials were selected to assess their biodegradation in the different test systems: polyhydroxybutyrate copolymer, a bacteria-derived, thus bio-based, biodegradable material as a positive control, polybutylene sebacate (PBSe), polybutylene sebacate co-butylene terephthalate (PBSeT), two polymers commonly used in blends for plastic products, and low-density polyethylene (LDPE) as the negative control (**Table 1**).

The materials were tested as films, due to technical constraints in the processing only available with different thicknesses. The positive control PHB, marketed under the product name Mirel P5001 (Metabolix, United States) was described as "PHA copolymer" by the producer and the exact polymer was not disclosed. Our FTIR spectral analysis (data not shown) confirmed the materials as PHB. In the lab tests, small pieces of film (4 × 4, 2 × 4, 3 × 3, ø 2 cm) were directly incubated in the test vessels. For the mesocosm and field tests polymer film samples were mounted in HYDRA® test frames (260 mm × 200 mm external and 200 mm × 160 mm internal dimensions leaving a surface of 320 cm^2 of material directly exposed), i.e., held between mesh (PET) and plastic frames (PE) (**Supplementary Figure 1**) to prevent mechanical impact on the sample, as described before (Lott et al., 2020).

Matrices Sediment and Seawater

Eulittoral sediment: Natural marine sediment for the eulittoral tests in the lab and in mesocosms was retrieved at about 0.1 m water depth from the beach of Fetovaia, Isola d'Elba, Italy, (42°44′00.1″N, 010°09′15.3″E) and is called "beach sediment."

TABLE 1 | List of tested polymers with their properties, film thickness, compounds, and supplier. Percentage of total organic carbon (TOC), total carbon (TC), hydrogen (H), and nitrogen (N) analyzed with standard methods.

Test material	Thickness, compounds, supplier	TOC (%)	TC (%)	H (%)	N (%)
Low Density Polyethylene **LDPE** (negative control)	Film 30 microns Grade: LUPOLEN 2420K, LyondellBasell	85.03	85.37	14.68	< 0.1
Polybutylene Sebacate **PBSe**	Film 25 microns aliphatic polyester	65.26	65.58	7.69	< 0.1
Polybutylene Sebacate co-butylene Terephthalate **PBSeT**	Film 25 microns aliphatic-aromatic polyester	65.25	65.81	9.54	< 0.1
Polyhydroxyalkanoate Copolymer **PHB** (positive control)	Film 85 microns Grade: Mirel^{TM} P5001, Metabolix, as by the producer: compound > 70% PHA copolymer (confirmed as PHB by FTIR), plasticizer, fillers	47.82	49.11	6.03	0.52

Sublittoral sand: Carbonate sediment for the benthic mesocosm tests was collected by divers from the seafloor at 40 m depth off Isola di Pianosa, National Park Tuscan Archipelago, Italy (42°34′41.4″N, 010°06′30.6″E), and is called "seafloor sediment." Larger pieces, like plant material, sea shells, pieces of driftwood, etc., were removed by sieving through a 10 mm mesh after collection. Seawater was taken at Secheto, Isola d'Elba, Italy (42°44′06.5″N, 010°10′33.5″E) and was used for the lab experiments, to wash the sediments and to fill the mesocosms. The mesocosm tests were run twice for about 1 year each and specified as y1 and y2 in this text. The matrices were renewed after the first run and the physical and chemical properties of sand and water were analyzed with standard methods at the beginning of each experiment (for details see Lott et al., 2020). The water used in the mesocosm tests (see below) had low to moderate levels of organic carbon, nitrogen and phosphor compounds, and chlorophyll. No toxic substances such as heavy metals, organotin compounds, or persistent organic pollutants (POPs) were detected. The beach sand used for tests was in the grain size range of medium sand and of mainly siliclastic origin. The seafloor sediment used for the benthic experiments was mainly carbonate fine sand. Porosity and permeability were slightly lower for both sand types in y2 (**Table 2**). Metal concentrations were low or below the detection limit. The test for persistent organic pollutants (POPs) in the sediments used for the experiments was negative (details in Lott et al., 2020).

Laboratory Tests

The lab tests were conducted at LeAF in Wageningen, Netherlands, with water and sediment from the Mediterranean field test locations (**Table 2**). The matrices were collected in plastic containers, shipped to LeAF and stored at 4°C until further use. At the start of the experiments, water and sediment were characterized with standard analytical methods.

Eulittoral Test (Beach Scenario)

The plastic samples were buried in 400 g of beach sediment under aerobic conditions as described in Tosin et al. (2012), following International Organization for Standardization (2019). The sediment had a water content of 18.9%, total solids content of 81.1%, of which volatile solids of 0.57%, total nitrogen of 7.4 mg/kg, and total carbon of 1.1 g/kg. No nutrients were added. The tests were carried out in 2-L Duran® wide-mouth bottles and a container for the CO_2 sorption connected to a side port. The container was filled with 30 mL of 0.5N KOH solution. The bottle and the container were closed with a Python rubber stopper (Rubber BV, Hilversum, Netherlands). The bottles were incubated in the dark in a closed box that was placed in a temperature-controlled room (20 ± 1°C). The test materials (PBSe and PBSeT) were square-shaped specimens with a dimension of approximately 40 mm × 40 mm. The negative control was done with 40 mm × 40 mm specimens of LDPE. For the test with PHB as the positive control specimens were cut in 20 mm × 40 mm pieces (because of the high grammage). The mass of each specimen (about 100 mg) was recorded. For the test 15 reactors were prepared to enable testing in triplicates of PBSe, PBSeT, PHB (reference material/positive control), LDPE (negative control), and blanks to correct for endogenous respiration. All reactors were pre-incubated without plastic samples to assess the endogenous respiration. After 1 week of pre-incubation, the CO_2 production was measured. The results showed that the endogenous respiration was similar in the bottles. After the pre-incubation, the test was started. For this, the reactors were opened and 100 g of sediment was removed. The sediment surface was smoothened and two specimens of test materials PBSe or PBSeT or LDPE or one specimen of PHB was placed on the surface. Thereafter the withdrawn sediment was carefully put on top of the sediment and test material. The specimens were covered with sand in a homogenous layer. The blanks for endogenous respiration did not receive any test specimen.

The extent of biodegradation [i.e., (endogenous) respiration] was assessed by determining the amount of carbon dioxide produced and absorbed in the KOH solution by titration with 0.3N HCl solution to pH 8 and thereafter further to pH 3.8. The amount of CO_2 absorbed was calculated according to the formula given by Tosin et al. (2012). The container for the CO_2 absorber was removed and analyzed and titrated before its capacity was exceeded. Each time the KOH was replaced by a fresh solution the reactor was weighed to monitor moisture loss

TABLE 2 | Experimental conditions: Properties of the water and sediments from the lab, field, and mesocosm experiments.

	LAB		MED Field						MED Mesocosm				ASIA Field		
	EUL	BEN	EUL		PEL	BEN			PEL	EUL		BEN	BEN		
	Medium EUL	Medium BEN	Porewater* EUL	Sediment EUL	Seawater PEL	Seawater BEN	Pore-water* BEN	Sediment BEN	Seawater PEL/BEN	Porewater EUL	Sediment EUL	Sediment BEN	Seawater BEN	Porewater* BEN	Sediment BEN
Grain size mean ± SD (µm)	278 ± 14	181 ± 23		y1: 214 ± 5 y2: 278 ± 5				213 ± 26			y1: 278 ± 14 y2: 206 ± 9	y1: 181 ± 23 y2: 146 ± 47			197 ± 47
Permeability mean ± SD (10^{-11} m^{-2})	17.9 ± 0.6	2.60 ± 0.6		y1: 7.46 ± 1.5 y2: 20.06 ± 2.0				1.12 ± 0.9			y1: 17.9 ± 0.6 y2: 9.54 ± 2.2	y1: 2.60 ± 0.6 y2: 2.40 ± 1.2			2.26 ± 0.8
Porosity mean ± SD	0.45 ± 0.2	0.62 ± 0.4		y1: 0.41 ± 0.2 y2: 0.43 ± 0.5				0.67 ± 0.6			y1: 0.45 ± 0.2 y2: 0.42 ± 0.8	y1: 0.62 ± 0.4 y2: 0.51 ± 0.6			0.54 ± 0.1
daily mean temperature [°C]	20 ± 1	20 ± 1	12–30, lowest −1.0 highest 38.4		14–25	14–20			20.5 ± 1	19.8 ± 1			28.6 ± 0.5	28.9 ± 0	
light PAR [% surface irradiance; µmol photons $m^{-2}s^{-1}$]	dark	dark			13%	3 %			11.3 µmol photons $m^{-2}s^{-1}$	dark			0.5 %		
salinity	38.5	38.5	mostly 36–42 0–70 in extremes		38.0 ± 0.1 38.4 ± 0.2	38.0 ± 0.1 38.3 ± 0.1			39.4 ± 0.3 39.6 ± 0.6	39.4 ± 0.3 39.6 ± 0.6			33.9 ± 0.2	34.1 ± 0.1	
pH	8.3	8.3	mostly 7.6–8.2, lowest 6.8, highest 9		y1: 8.19 ± 0.02 y2: 8.15 ± 0.08	y1: 8.18 ± 0.05 y2: 8.19 ± 0.07			8.1 ± 1	8.1 ± 0.02			8.1 ± 0.1	7.9 ± 0	

(Continued)

TABLE 2 | Continued

	LAB		MED Field						MED Mesocosm				ASIA Field		
	EUL	BEN	EUL		PEL	BEN			PEL	EUL		BEN	BEN		
	Medium EUL	Medium BEN	Porewater* EUL	Sediment EUL	Seawater PEL	Seawater BEN	Pore-water* BEN	Sediment BEN	Seawater PEL/BEN	Porewater EUL	Sediment EUL	Sediment BEN	Seawater BEN	Porewater* BEN	Sediment BEN
oxygen saturation [% atm.]	unstirred	unstirred	mostly 20–80, rarely 100		y1: 97.4 ± 5 y2: 103.1 ± 6.3	y1: 97.1 ± 4 y2: 100.9 ± 7.7			98 ± 2	97.3 ± 1.6			101.3 ± 6.8	28.2 ± 11.2	
nutrient-related parameters**	TN 7.4 mg/kg TC 1.1 g/kg no nutrients added	TN 308 mg/kg, TC113 g/kg no nutrients added	low to moderate	low or b.d.l.	low	low	low	low or b.d.l.	low or b.d.l.	low or b.d.l.	low or b.d.l.	low or b.d.l.	low	low	low or b.d.l.
Chlorophyll a Phaeophytin [µg/l]			3.03 ± 1.85 3.22 ± 1.39		b.d.l. 1.37 ± 0.86	b.d.l. 1.5 ± 1.27			1.38 ± 1.37 1.86 ± 1.16	2.14 ± 1.07 5.21 ± 2.26			1.4 ± 0.7 6.7 ± 5.1		
metals			low Fe, Mn, Al; no toxic heavy metals (b.d.l.)	low Zn, Ni, Cr, others b.d.l.	low Al, Fe, Mn, others b.d.l.	low Al, Fe, Mn, others b.d.l.	low Fe, Mn, others b.d.l.	low Fe, Mn, Pb, Cr, others b.d.l.	low Fe, Mn, Pb, Cr, others b.d.l.	low Fe, Mn, Pb, Cr, others b.d.l.	low Fe, Mn, Pb, Cr, others b.d.l.	low Fe, Mn, Pb, Cr, others b.d.l.	low Al, Fe, Mn, others b.d.l.	low Fe, Mn, others b.d.l.	low Fe, Mn, Pb, Cr, others b.d.l.
organotin			b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
POPs			b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.

*Porewater was taken at 5 cm sediment depth; **nutrient-related parameters sensu Weber et al. (2012), LAB, laboratory tests; MED, Mediterranean Sea; ASIA, tropical SE Asia; EUL, eulittoral (beach scenario); BEN, benthic (sublittoral sand bottom scenario); PEL, pelagic (open water scenario); low, values just above detection limit; moderate, values within one order of magnitude of detection limit; b.d.l., below detection limit; gray shaded fields, not analyzed; TN, total nitrogen; TC, total carbon; PAR, photosynthetically active radiation (400–1,000 nm); POPs, persistent organic pollutants.

from the sediment and allowed to sit open for approximately 15 min so that the air in the reactor was refreshed before resealing the reactor. Distilled water was added back periodically to the sediment to maintain the initial weight of the reactor. The tests were terminated after 331 days.

Benthic Test (Seafloor Scenario)

The biodegradation under aerobic conditions at the water-sediment interface was tested following Tosin et al. (2012) and International Organization for Standardization (2016). At the start of the experiments, the medium used for the benthic lab test had a pH of 8.3, a water content of 95.8%, a total solids content of 4.2%, of which volatile solids were 15.7%. The tests were carried out in 250 ml Erlenmeyer flasks with a container attached to a side port filled with 3 mL 0.5 N KOH for CO_2 absorption. The bottle and the container were closed with a Python rubber stopper (Rubber BV, Hilversum, Netherlands). The bottles were incubated in the dark in a closed box that was placed in a temperature-controlled room (20 ± 1°C). The test materials (PBSe and PBSeT) were square-shaped specimens with a dimension of approximately 30 mm × 30 mm. The negative control was done with a specimen of LDPE. For the test with PHB as the positive control specimens were cut in circles of 20 mm diameter. The mass of each specimen (about 36 mg for PHB, about 25 mg for the others) was recorded. For the test 15 reactors were prepared to enable testing in triplicates of PBSe, PBSeT, PHB [reference material/positive control, LDPE (negative control)], and a blank without test material to correct for endogenous respiration. Sediment (30 g) was placed at the bottom of each reactor with 70 ml seawater and 3 ml of 0.5N KOH (the CO_2 absorbing solution) was introduced in the container. Endogenous respiration was measured after 1 week by measuring the CO_2 production. The results showed that the endogenous respiration was similar in the bottles. After the initial week of pre-incubation, the test was started. For this, the reactors were opened and the specimen of test materials PBSe or PBSeT or LDPE or PHB were placed on top of the sediment. About 25–35 mg of test material or LDPE or PHB was introduced in the reactors. The blanks for endogenous respiration did not receive any test specimen. The carbon dioxide produced in each reactor reacted with KOH and was titrated as described above. The tests were run for 331 days. The content of the test bottles was sacrificed for the retrieval of remaining plastic test items after the termination of the test.

Modeling the Half-Life $t_{0.5}$ of Biodegradation

For all statistical analyses, R project was used (R Core Team, 2020). From the raw data of CO_2 release over time (equaling aerobic biodegradation) the half-life of the polymer was analyzed using Three Parameter Logistic Regression (3PL) by fitting the data with a non-linear model (package *nlme*) to the formula:

$$y(t) = y_{max} + \frac{-y_{max}}{1 + \left(\frac{t}{c}\right)^b} \quad (1)$$

where y is the polymer biodegradation in percent, t the corresponding time in days, and y_{max}, b, and c the curve parameters estimated by the model and representing the biodegradation at the plateau, the slope-factor and the inflection-point of the curve, respectively (adapted from Junker et al., 2016). Since the same test flask was measured repeatedly over time, the data is not independent. However, independence of the observations is an important assumption for this statistical analysis. Therefore, the replicate ID was included as a random factor, which allowed different estimated values for y_{max} for each flask. If no model parameters could be estimated, y_{max} was below 0 (as for LDPE), and/or estimated parameters (except y_0) were not significantly different to 0 no biodegradation was assumed. To visualize the confidence interval (CI) of the predicted disintegration curves, a Monte Carlo simulation approach was employed to re-sample for each x value (days) 50,000 predicted values (% biodegradation) considering the estimates and variance of model parameters. The range of the 95% percentile of these samples was considered as 95% confidence interval. Before calculating the half-life, it had to be tested if y_{max} was higher than 50 %. Therefore, empirical p-values were used. 500,000 values for y_{max} were re-sampled considering the coefficients predicted by the non-linear model and its variance. If less than 5% of these values were below 50%, the plateau was assumed to be greater than or equal to 50%. If this condition was fulfilled, 500,000 values for the half-life ($t_{0.5}$) were generated by setting y in the 3PL equation to 50%, using the estimated values and corresponding variances of the model parameters, and solving the formula to t. In some cases, the half-life could not be calculated as described because y_{max} assumed values were below 50% (however, in less than 5% of the cases, as shown by the previous test). In these cases, the half-life was set to infinity. To compare calculated values for $t_{0.5}$ between habitats and experiments, the difference between two groups of $t_{0.5}$ values was calculated. For these pairwise comparisons, empirical p-values were calculated by $p = \frac{2r}{n}$, where r is the number of $t_{0.5}$ differences either above or below zero and n the number of trails (i.e., 500,000). If all r values were below or above 0, the lowest possible value for p was assumed ($2 \cdot 1/n = 4 \cdot 10^{-6}$). p-values were adjusted for multiple comparisons using the Holm method (Holm, 1979). The distributions of the re-sampled half-life values were visualized by violin plots in which the spread along the x axis represents the frequency of values on the y axis (half-life). Different letters indicate significantly different groups.

Mesocosm Tests

The mesocosm tests were conducted in two consecutive years (y1 and y2) in triplicates in a climate chamber as described before (Lott et al., 2020). Three coastal habitats were simulated in a tank system consisting of two 630-L plastic containers placed on top of each other. The upper tank contained a layer of siliclastic beach sediment in which the samples were buried (eulittoral scenario) and which was flooded with seawater every 12 h. The bottom of the upper tank was perforated to allow the water to slowly drain to the lower tank, thus mimicking a 12-h tidal cycle at the samples. The lower tank contained a layer of carbonate seafloor sediment on which samples for the benthic test were placed. The pelagic test was performed by hanging samples in the water column of the lower tank, which was illuminated on a 12:12 h rhythm. The bulk water of the two tanks was connected by pipes and constantly moved by additional pumps in the lower tank. The water was regularly checked for salinity, pH, and oxygen saturation and compensated for evaporation loss by adding demineralized water if necessary. The temperature was 20.5°C ± 1°C and mean light intensity on the sediment surface of the benthic tests was 11.56 μmol photons·m^{-2}·s^{-1}. Salinity was 39 ± 1. The pH was 8.1 ± 0.1. The oxygen concentration was close to air saturation (98 ± 2%). In the first year (y1), three polymers were tested in the mesocosm experiments: LDPE, PHB, and PBSeT were sampled at four time points (t1–t4) (**Supplementary Table 1**). In the second year (y2), PBSe was tested additionally and sampled at two time points (t1 and t3). Three to five samples were retrieved ca. every 2.5 months from the tanks. The last sampling interval of the y2 experiment was only 1.5 months.

Field Tests

Field tests were performed in the eulittoral (beach scenario), the pelagic (open water scenario), and the benthic (sublittoral seafloor) (**Figure 1**) as described before (Lott et al., 2020).

For environmental conditions at each site see **Table 2**. For sampling dates and intervals see **Supplementary Table 2**.

Eulittoral Tests

The eulittoral tests were set up on the Island of Elba, Terme di San Giovanni, Portoferraio (N 42°48′12.1″N, 010°19′01.0″E, Italy in a former saline basin, now open to the sea (Lott et al., 2020). The test system consisted of 60-L plastic bins filled with beach sediment in which the samples were buried. To simulate an intertidal sandy beach the bins were placed on wooden racks in the midwater line in a way that the samples were exposed to changing conditions of being wetted and falling dry with the tides.

Pelagic and Benthic Tests

The pelagic and benthic field tests in the Mediterranean Sea were performed in the marine protected area of the National Park Tuscan Archipelago off the Island of Pianosa (42°34′41.4″N, 010°06′30.6″E), Italy. The benthic field tests in South-East Asia were performed in Sahaong Bay (01°44′35.4″N, 125°09′09.3″E), Pulau Bangka, NE Sulawesi, Indonesia. For details see Lott et al. (2020).

The pelagic test systems consisted of a rack to which the sample frames were attached, anchored to stay afloat at a water depth of 20 m, chosen to avoid influence by surface wave activity. For the benthic tests, the samples were mounted to a flat panel which was fixed to the seafloor at 40 m in the Mediterranean Sea and to 32 m in Indonesia. These depths were chosen to avoid interference of the experiments with the seagrass meadows or coral reef structures, respectively.

In the Mediterranean field tests, in the first run of field experiments (y1) in all three habitats five replicates of PHB, PBSeT, and LDPE were exposed and sampled about every 2.5 months. One additional set was left exposed for 2 years (t_5), together with new samples for a second 1-year run (**Supplementary Table 2**). From these additional sets, two replicates were sampled from the pelagic and benthic experiment after 678 days and five replicates were sampled from the eulittoral test system after 686 days. In the second experiment run (y2), the number of replicates per time was reduced to three. Also, PBSe was added as test material with three replicates in the pelagic and benthic tests, and two replicates per time in the eulittoral test. The data from y1 and y2 were pooled in the analysis as experiment y1 followed the same seasonality as y2.

In the wet tropics of South-East Asia, tests were conducted in 2017 and 2018. Three replicates of PHB, PBSe, and PBSeT were exposed to the benthic habitat. Sampling occurred after 19, 48, 62, 90, and 310 days for PHB, after 16, 90, 130, and 310 days for PBSe and after 90 and 310 days for PBSeT.

Sampling and Data Acquisition From Mesocosm and Field Tests

At the given time interval, the sample frames were carefully detached from their racks (pelagic, benthic) or dug out of the sediment (eulittoral), rinsed in ambient water, packed singly in plastic (PE) bags covered with water, and brought to the laboratory for further treatment the same day. Each frame was opened and the sample photographed in a standardized way. Then the samples were washed in freshwater and left to dry at room temperature overnight.

Disintegration Measurements

In the open-system tests of the mesocosm and field experiments, material disintegration was determined as a proxy for biodegradation assuming that the samples were protected from mere physical damage well enough by the construction of the test frame. The degree of disintegration (% area loss) of each sample was determined photogrammetrically. Dried samples (Mediterranean tests) were scanned on a LIDE 210 flatbed scanner (Canon Inc.). For the Indonesian samples, photos (Canon EOS 5D MkII) of the freshly sampled films were used and analyzed for the proportion of lost vs. still intact surface using the software ImageJ[1].

Calculating Half-Life $t_{0.5}$ Based on Disintegration Data

The data from the field and mesocosm experiments was analyzed in a different way than described for the lab test. Far fewer data points were acquired in the field and mesocosm tests than in the lab experiment, therefore we chose a linear model with less degrees of freedom (i.e., estimated parameters) over the non-linear logistic regression used to analyse the lab data. The disintegration of the polymer area over time was analyzed using beta regression (package *betareg*) because response values consisted of percent data. The extreme values of 0% and 100%, were transformed according to Smithson and Verkuilen (2006). At the start of the experiment (t = 0 days), no disintegration was assumed, therefore n artificial values with 0% disintegrated area were included, where n is the number of replicates in the data-subset. For each habitat and experiment (field vs. mesocosm) one model was applied. For the mesocosm experiment, additionally, the influence of the year of the experiment was analyzed and integrated into further analysis if a significant interaction with the variable time existed. Different models were applied

[1] https://imagej.nih.gov/ij/

FIGURE 1 | Field test systems: left: eulittoral test: Samples were exposed in bins filled with beach sand on a rack in the midwater line, center: pelagic tests: samples attached to a floating rack exposed at 20 m water depth, right: benthic tests: samples were mounted in panels that were fixed on the sandy seafloor at 40 m (Mediterranean Sea) and 32 m water depth (SE Asia).

using logit, cloglog, cauchit, and loglog link-functions (see **Supplementary Table 3**). The best model was then selected by comparing the Root Mean Square Deviation (package *caret*). When comparing the disintegration rate between habitats it is not sufficient to only compare the slopes. The non-linear shape of the back-transformed disintegration curve depends on both, the *y*-intercept *a* and the slope *b*. Therefore, rather half-life ($t_{0.5}$) should be compared. Since different link-functions were used, different formulas had to be applied to calculate the corresponding *x* (time) values at which the disintegration reached 50 %. For example, in the case of *logit*-transformed data, 50 % of the material is left at the *x*-intercept of the regression curve for transformed data:

$$\text{logit}\,(50\%) = \log\left(\frac{p}{1-p}\right) = \log\left(\frac{0.5}{1-0.5}\right) = 0 \qquad (2)$$

The *x*-intercept can be calculated by $t = \frac{-a}{b}$. The formulas used for the other link-functions are compiled in **Supplementary Table 3**. A Monte Carlo simulation approach was applied to re-sample 500,000 values for *a* and *b* considering model parameter estimates and variance and a normal distribution. The comparison of the generated half-life was performed with empirical *p*-values as described for the lab experiment.

RESULTS

Laboratory Tests With Mediterranean Sea Matrices

The lab tests with matrices from two of the shallow water habitats chosen for field and mesocosm tests were done to prove the biodegradability of the three tested polymers PHB, PBSe, and PBSeT under optimized lab conditions with natural matrices. The eulittoral test (beach scenario) and the benthic test (seafloor scenario) were selected because the tested polymers have a higher specific density than seawater and will sink to the seafloor. The pelagic test was not performed due to space limitations in the laboratory. The biodegradation in both habitats was fastest for PHB and similar for PBSeT and PBSe (**Figure 2**).

In the benthic test, a plateau was reached or nearly reached after about 1 year for the three test materials. PHB was more or less completely converted to CO_2 as is evidenced by the 81% biodegradation that was calculated from the CO_2 production. The biodegradation percentage of PBSe and PBST was 71 and 76%, respectively, which also indicates that mineralization of these test items was almost complete, given that an incorporation of about 25–30% of substrate carbon into microbial biomass is assumed [see e.g., Payne (1970) for conversion rates in bacterial cultures]. Except for LDPE none of the plastic test items could be retrieved, not even in fragments, from the benthic test bottles which indicates that the disintegration of the test items was complete. In some cases, e.g., for PBSe very small particles were visible but these were in the size range of sand grains. LDPE was recovered intact from the flasks and biodegradation was not detected. In the eulittoral test, none of the three materials reached the plateau phase within the duration of the experiment (331 days). PHB was completely disintegrated in all flasks. For both, PBSe and PBSeT, one of the three replicates could be retrieved degraded to 25 and 33%, respectively.

The respective half-lives $t_{0.5}$ predicted by the model are given in the following text without the confidence intervals which can be found as a summary in **Table 3** at the end of the results section. For PHB in the benthic test, the half-life was 116 days and significantly ($p < 0.001$) lower than in the eulittoral test (222 days, **Figure 3**). For PBSe, the modeled $t_{0.5}$ was 203 days and for PBSeT 187 days both in the benthic test. In the eulittoral test, the exposure time for both materials was not sufficient to reach a biodegradation of more than 50%, therefore modeling $t_{0.5}$ was not possible.

Mesocosm Tests With Mediterranean Sea Matrices

All test materials, except LDPE, showed disintegration with high heterogeneity between replicates, habitats, and material type. About 90% disintegration was observed for PBSe and PBSeT in the eulittoral test in y2 after 238 days (**Figure 4**) and for PBSeT in the pelagic test in y2 after 271 days. Most samples of PBSe and PBSeT in the other habitats were disintegrated less than 50% after 308 and 270 days of exposure, respectively.

The half-life of PHB did not differ between the two experiments (year 1 and year 2) within each habitat. The predicted half-life in the benthic habitat (357 days) was significantly lower than in the eulittoral (737 days) and pelagic

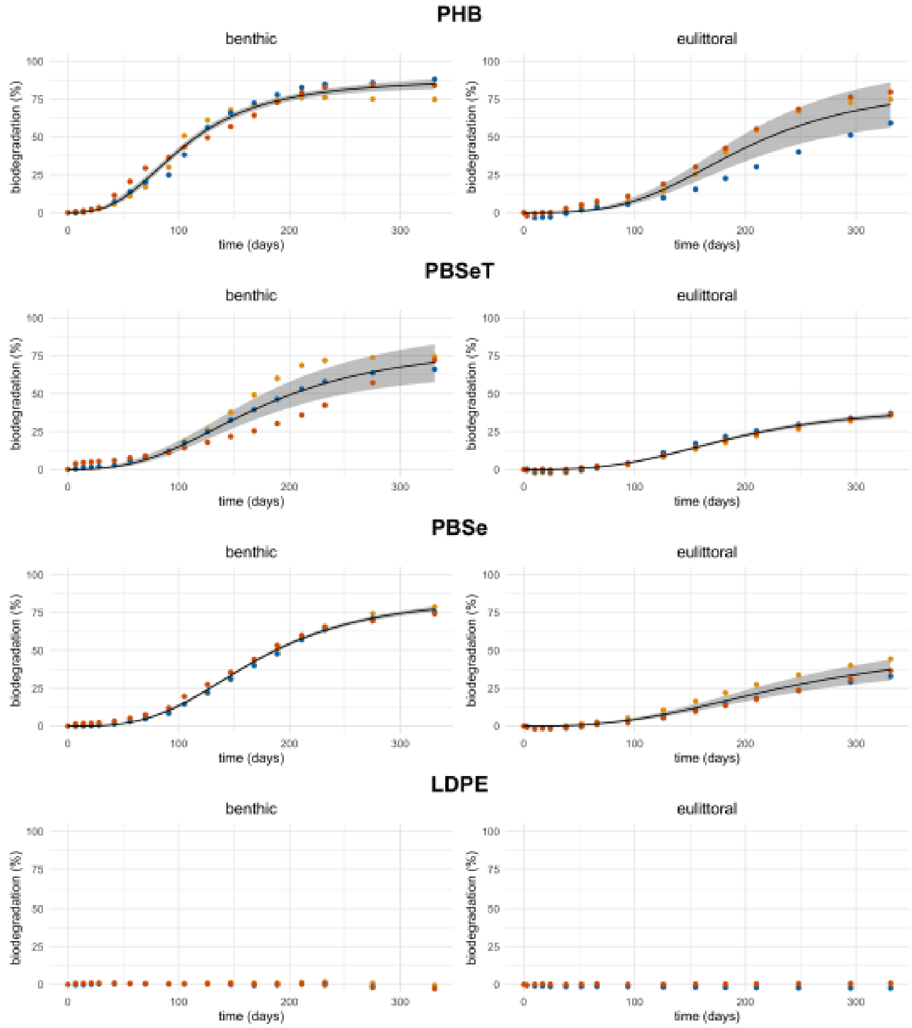

FIGURE 2 | Laboratory experiments with Mediterranean Sea water and sediment: Biodegradation curves of PHB, PBSe, and PBSeT when incubated with seafloor sediment at the sediment-seawater interface (benthic) and buried in beach sand (eulittoral). Colors red, yellow, and blue indicate samples from different test flasks, dots represent raw data analyzed in the model. The model curve ± 95% CI (shaded area) was drawn if estimated parameters were significantly different from 0.

(1,247 days) habitats (**Figure 5**, **Table 3**, and **Supplementary Table 4**). PBSeT had a $t_{0.5}$ of 778 days in y1 and 446 days in y2 in the benthic tests, 365 days in y1 and 147 days in y2 in the eulittoral tests, and 532 days in y1 and 224 days in y2 in the pelagic tests (**Figure 5** and **Table 3**). In the eulittoral experiment, the degradation was significantly faster in the second-year experiment than in the first-year experiment (p = 0.0071). No significant differences were detected between both experiments (y1 and y2) in the benthic and pelagic tests (**Supplementary Table 5**). The half-life of PBSe was significantly higher in the

TABLE 3 | Summary of all tests: Half-lives $t_{0.5}$ of PHB, PBSe, and PBSeT as predicted by statistical modeling of the experimental data.

Polymer (thickness)	Habitat	Year	Lab (20 ± 1°C)	Mesocosm (20.5 ± 1°C)	Mediterranean Sea (*12–30°C)	SE Asia (28.5 ± 0.5 °C)
PHB (85 μm)	Benthic		115.9 (111.5, 120.2)	356.8 (277.3, 534.0)	653.7 (633.6, 671.2)	54.3 (48.9, 59.7)
	Eulittoral		221.5 (194.2, 276.3)	736.7 (537.1, 1,320.0)	417.1 (332.4, 584.2)	
	Pelagic			1,246.7 (857.8, 2,584.4)		
PBSeT (25 μm)	Benthic	1	203.3 (176.6, 252)	777.5 (431.6, 1,328.3)	797.1 (743.9, 875.0)	200.7 (183.5, 216.2)
	Benthic	2		445.6 (391.5, 1,219.0)		
	Eulittoral	1		364.9 (178.2, 600.5)	703.7 (688.0, 724.3)	
	Eulittoral	2		146.8 (121.1, 351.4)		
	Pelagic	1		531.8 (265.6, 1,091.8)		
	Pelagic	2		223.8 (207.6, 290.6)		
PBSe (25 μm)	Benthic		187.2 (183.9, 190.5)	2,614.2 (2,096.6, 3,486.8)	1,412.6 (956.7, 3,121.1)	99.2 (93.0, 106.8)
	Eulittoral			148.2 (132.9, 165.6)	1,209.1 (686.2, 5,177.3)	

*The range of the confidence interval CI (centered 95-percentile of the Monte Carlo simulations) is given in brackets. *temperature range (daily mean): pelagic 14–25°C, benthic 14–20°C, eulittoral 12–30°C*

benthic tests (2,614 days) than in the eulittoral test (148 days, $p < 0.0001$, **Figure 5**, and **Table 3**). Predictions for the half-life of PBSe in the benthic test should be considered with caution, since maximum degradation after 237 days was 1.5%, making predictions of the time needed until 50% is degraded unreliable. In the pelagic test, no significant disintegration was measured for PBSe. For LDPE no disintegration at all was measured in any test during the exposure time thus it was not possible to model $t_{0.5}$.

Field Tests

Mediterranean Sea

All test materials, except LDPE, showed signs of disintegration when in contact with sediment, i.e., in eulittoral and benthic tests (**Figure 6**). In the pelagic tests, no disintegration was observed for PHB and PBSe within 2 years. For PBSeT, material disintegration increased significantly over time, but at a very low slope. The maximum disintegration after 676 days was only 1.01% and 0.13%, therefore we did not predict the half-life. The heterogeneity between replicates was high. The half-life $t_{0.5}$ of PHB in the benthic test (654 days) was significantly higher ($p = 0.0161$) than in eulittoral test (417 days, **Figure 7**, **Table 3**, and **Supplementary Table 6**). In the pelagic test, modeling of $t_{0.5}$ was not possible because no disintegration was measured during the exposure time. PBSeT had a $t_{0.5}$ of 797 days in the benthic test, which was significantly lower than in the eulittoral test (704 days, **Figure 7**, **Table 3**, and **Supplementary Table 7**). PBSe had a $t_{0.5}$ of 1,413 days in the benthic test and of 1,209 days in the eulittoral test (**Figure 7**, **Table 3**, and **Supplementary Table 8**).

SE Asia

All test materials, except LDPE, fully disintegrated in the benthic test within few months (**Figure 8**) with heterogeneity between replicates. The $t_{0.5}$ for PHB was 54 days, for PBSeT 201 days, and for PBSe 99 days (**Figure 7** and **Table 3**). The disintegration of all polymer types was significantly faster in SE Asia compared to the Mediterranean Sea (**Figure 7** and **Supplementary Tables 6–8**).

Summarized (**Table 3**), in the field tests in the Mediterranean Sea, the $t_{0.5}$ of a 25 μm thick film of PBSeT and PBSe and an 85 μm thick film of PHB ranged between 1.8–3.9 years in the benthic tests (seafloor scenario) and 1.1–3.3 years in the eulittoral tests (beach scenario). No significant disintegration occurred for any of the materials in the pelagic tests (water column scenario). In the benthic test in SE Asia, $t_{0.5}$ was about 0.15 years (2 months) for PHB, 0.55 years (7 months) for PBSeT, and 0.27 years (4 months) for PBSe. For LDPE no disintegration was measured, thus no half-life was possible to calculate.

DISCUSSION

The aim of this study was to prove the biodegradability of biodegradable polymers under laboratory conditions, to test the biodegradation performance under natural field conditions, and in a tank test system with natural matrices.

We tested the performance of PHB (as reference material and positive control), PBSe, and PBSeT in three different habitat scenarios, namely the intertidal sandy beach (eulittoral), the sandy sublittoral seafloor (benthic), and the open water column (pelagic) in a three-tier test approach in closed-vessel laboratory, in mesocosm tank and in-situ field tests, some of which in two

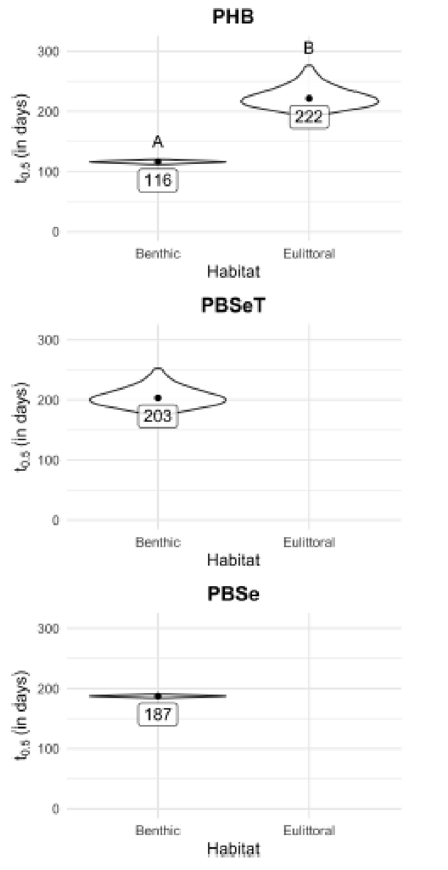

FIGURE 3 | Laboratory experiments with Mediterranean Sea water and sediment: Biodegradation half-lives $t_{0.5}$ of PHB, PBSe, and PBSeT. Monte Carlo simulations of half-life for tested polymers in two habitats, on the seafloor at the sediment-seawater interface (benthic) and the beach scenario (eulittoral). Shown is the distribution of the centered 95 percentiles of the simulations as violin plots. The dot in the center of each violin represents the half-life as calculated from the estimated model coefficients; the value is given in the box below. Letters above the violin plot represent the results of the multiple comparisons. Different letters (A, B) indicate significantly different groups (i.e., Holm-adjusted *p*-value below $\alpha = 0.05$). For PBSeT and PBSe in the eulittoral habitat, no half-life could be calculated because the plateau phase was not reached and values remained below 50 % (cf. **Figure 2**).

different climate zones (the warm-temperate Mediterranean Sea and the tropical sea of SE Asia).

Furthermore, we introduced an analytical tool based on statistical modeling to predict the specific half-life calculated from the experimental data for each set of test conditions, to use the half-lives to numerically compare the performance of three different materials tested, and to numerically compare the performance of one material in different environmental settings.

The three-tier approach to test the performance of biodegradable plastic in the marine environment gave a comprehensive view and could differentiate between sediment type, habitat, and climate zone.

Half-lives $t_{0.5}$ Differed Between the Materials in All Test Systems and Habitats

Laboratory Experiments

In the lab tests, biodegradation of PHB was faster in the benthic than in the eulittoral test and similar to the results obtained by Briassoulis et al. (2020) in a comparable setting. For PBSe and PBSeT in the eulittoral tests the plateau phase of biodegradation, as calculated by CO_2 evolution, was not reached within the test period and values remained below 50 %. Consequently, $t_{0.5}$ could not be calculated. The leveling out of the biodegradation curves in the benthic test (**Figure 2**) indicates a limitation of substrate for the bacteria and the nearly complete conversion of the polymer into CO_2 and microbial biomass. In the humid sand of the eulittoral tests, the CO_2 production rate was generally lower than at the submersed sand surface in the benthic test. However, the fact that in most of the experiments no or only little test material was left could indicate a more efficient build-up of microbial biomass in the eulittoral, a (yet) incomplete mineralization of soluble intermediates of biodegradation, a limitation of nutrients or inhibition by a hypothetical starvation factor as proposed by Mistriotis et al. (2019) in soil.

For PHB, both lab tests applied showed the biodegradability of the positive control but also revealed significant differences in the performance under the different experimental conditions of a simulated seafloor (benthic) and a simulated beach (eulittoral). The lab tests were conducted under static conditions without stirring or shaking the medium leaving the system purely diffusion-driven. It can be assumed that oxygen availability to the acting microbes was most of the time limited. This is also corroborated by the observation of black spots on the sediment below some of the samples in the benthic test indicating the precipitation of dark metal salts under anoxic conditions. As the methods for both tests are defined as aerobic (Tosin et al., 2012; International Organization for Standardization, 2019; International Organization for Standardization, 2016) some technical modifications as e.g., gentle stirring as proposed by Briassoulis et al. (2020) could be considered to assure the medium is well oxygenated.

Although both tests worked well it is recommended to use the test scenario that is most environmentally relevant for the purpose and to choose well the matrices, especially the sediment used. Sediments of different origin and quality most likely will differ in their microbial activity.

Mesocosm Experiments

The testing of the biodegradation of plastic in mesocosms of a larger volume was demonstrated as a viable complement

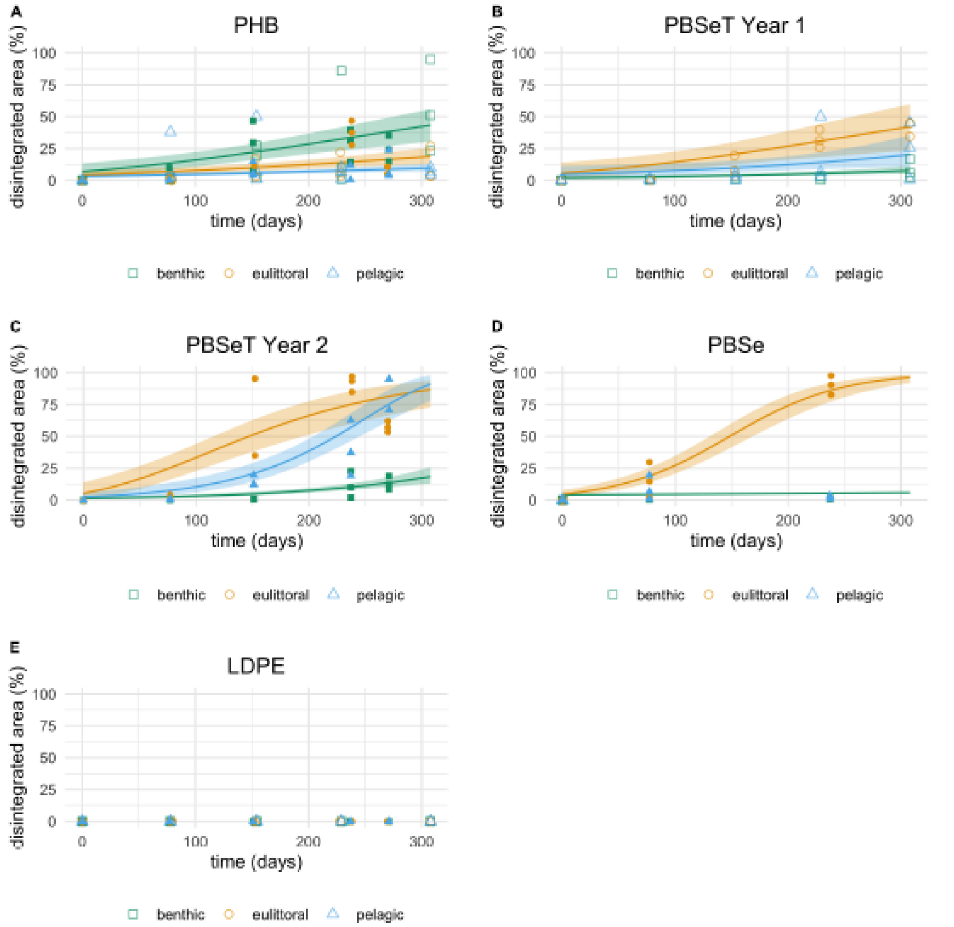

FIGURE 4 | Mesocosm experiments with Mediterranean Sea water and sediment: Disintegration curves of **(A)** PHB, **(B)** PBSeT, and **(C)** PBSe over 10 (year 1) and **(D)** 9 (year 2) months when exposed in the seafloor scenario at the sediment-seawater interface (benthic), in the water column (pelagic) scenario or buried in the intertidal sandy beach (eulittoral) scenario. **(E)** For LDPE no disintegration was measured. The model curve ± SE (shaded area) was drawn if the slope was different from zero and positive. Dots represent raw data analyzed in the model (open = year 1, filled = year 2). For PBSeT two significantly different model curves are shown. Colors represent the habitat (green = benthic, orange = eulittoral, blue = pelagic).

or even alternative to field tests and allowed tests with natural matrices without access to running seawater (Lott et al., 2020). The $t_{0.5}$ of the three polymers modeled from disintegration measurements in the open system tests in mesocosms (**Figure 5**) were about two to four times higher (excluding PBSe, see below) than the ones calculated from the CO_2 evolution in the lab tests (**Figure 3**) with the same temperature applied, which confirms the laboratory tests as optimized compared to field tests (even though oxygen availability might have been varying). This fact also confirms our assumption that using the degree of disintegration of samples that are well protected from physical impact as a proxy for biodegradation is well suited to measure the biological processes at the material in the open systems of mesocosms and field experiments rather than a mere physical deterioration of the plastic.

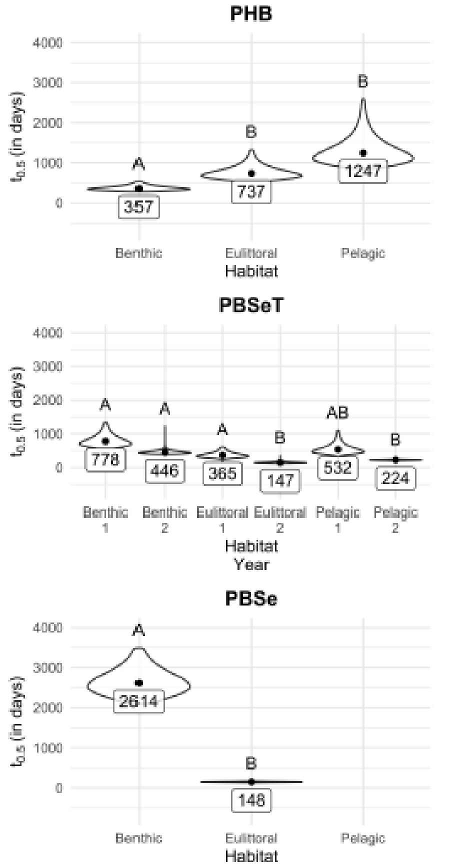

FIGURE 5 | Mesocosm experiments with Mediterranean Sea water and sediment: Disintegration half-lives $t_{0.5}$ of PHB, PBSeT, and PBS. Monte Carlo simulations of half-life for tested polymers in three habitats (on the seafloor at the sediment-seawater interface (benthic), the beach (eulittoral), and the water column (pelagic) scenario). Shown is the distribution of the centered 95 percentiles of the simulations as violin plots. The dot in the center of each violin plot represents the half-life as calculated from the model coefficients, and the value is given in the box below. Letters above the violin plot represent the results of the multiple comparisons. Different letters indicate significantly different groups.

In the mesocosm tests, the variability in the degree of disintegration of single specimens was high even within one tank system, but also between the three replicate tanks and between years, reflected in the sometimes wide 95% confidence intervals (CI) (**Figure 4**) as a common feature of all tests. This is attributed to the patchiness of the microbial community, also known from natural sediment environments (e.g., Böer et al., 2009). As can be seen from the shape of the violin plots, the variability within one test is higher in most of the scenarios where degradation was slower, thus half-life higher. For most tests, we applied a set of triplicates for each sampling interval which was just sufficient to obtain a statistically significant basis for modeling. However, this is the absolute minimal replication. Leaving a part of the samples longer deployed in the field tests than planned, led to an insufficient replication, especially considering the high variability observed in all tests. We therefore recommend using 4 or 5 replicates per interval to balance for variability. Furthermore, as seen when comparing the predictions from Asia and the Mediterranean Sea, the estimation of half-life is more precise when higher disintegration (at least about 75%) is reached.

Although observationally different, half-lives were not significantly different between the benthic and eulittoral habitat for the positive control PHB. Also for PBSeT, no consistent significant differences could be found for the half-lives between habitats. Only in the eulittoral test, the half-life in year 2 was significantly lower than in year 1. PBSe showed significantly different half-lives in the benthic and the eulittoral tests. However, very low values for the maximum disintegration in the benthic habitat (1.7% after 237 days) make the prediction of the half-life for this treatment unprecise and the $t_{0.5}$ predicted by the model should be taken rather as a rough indication and interpreted with caution. Comparing the performance of the three biodegradable materials in the different mesocosm tests the positive control PHB did disintegrate fastest in the benthic habitat whereas PBSe and PBSeT disintegrated fastest in the eulittoral habitat.

Field Tests

The half-lives in the Mediterranean field tests were higher than in the lab for the benthic test for all three polymers, about six times for PHB and about four and eight times higher for PBSe and PBSeT in the eulittoral, respectively. The field test in the Mediterranean Sea revealed significant differences between habitats and, compared with the tests in SE Asia, between climate zones. For all three biodegradable polymers PHB, PBSe, and PBSeT, disintegration was faster in the eulittoral than in the benthic. No significant disintegration was observed in the ultraoligotrophic setting of the Mediterranean pelagic. In the open water of the pelagic, the abundance of microbes is several magnitudes less (e.g., Schmidt et al., 1998) than in seafloor sediments, thus the overall activity of the microbial community is considered much lower. In the tropical waters of SE Asia, disintegration in the benthic was four to fourteen times faster than in the tests in the Mediterranean at the Island of Pianosa.

Marine (and aquatic) biodegradation tests in general often use water as the only matrix (e.g., ASTM, 2017) and give low rates as results (e.g., Bagheri et al., 2017). For biodegradable plastics, we consider this test scenario as the least environmentally relevant given that most biodegradable polymers have a density higher than water and will sink (or float at the water surface if the bulk density of a plastic object (e.g., a closed bottle or foamed material) is <1). However, a water column test is motivated

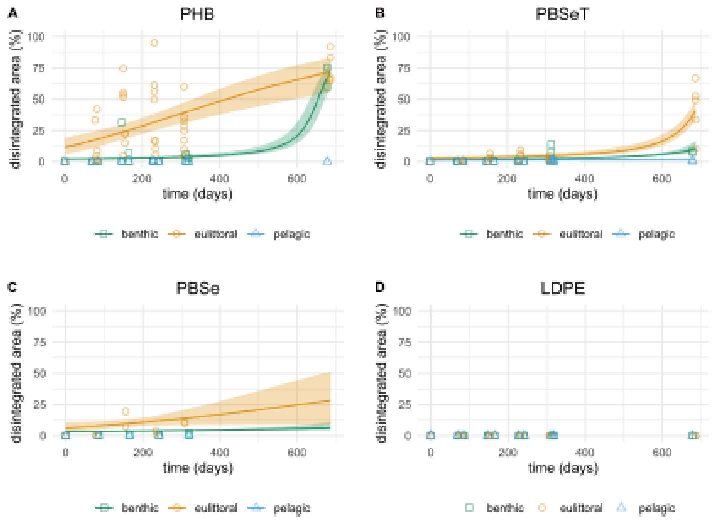

FIGURE 6 | Field experiments in the Mediterranean Sea: disintegration curves of **(A)** PHB, **(B)** PBSeT, and **(C)** PBSe when exposed on the seafloor at the sediment-seawater interface (benthic), the beach (eulittoral) and the water column (pelagic) scenario. **(D)** For LDPE no disintegration was measured. The model curve ± SE (shaded area) was drawn if the slope was different to zero and positive. Dots represent raw data analyzed in the model. Colors represent the habitat (green = benthic, orange = eulittoral, blue = pelagic).

for plastic items typically applied in the open water such as in aquaculture or fisheries.

Temperature Differences Explain Well Different Biodegradation Rates

Temperature is considered one of the most important environmental factors influencing the biodegradation rate. Pischedda et al. (2019) found a significant exponential relation between temperature and the biodegradation rate of a biodegradable plastic material in lab experiments with soil, in accordance with the Arrhenius equation, with the limitation of only three data points and thus no degree of freedom. For a rough estimation of the relationship between biodegradation rate and temperature in our experiments, we therefore applied an exponential model (**Figure 9**), confirming a significant negative relationship [$F(1, 8) = 17.654$, $p < 0.003$] between the predicted half-life and the average temperature in the mesocosm and field tests (Asia = 28.5°C, Mediterranean = 17.5°C, Mesocosm = 20.5°C). To increase datapoints to a more reasonable number, we did not differentiate between the different polymer types.

Other Factors That Determine Biodegradation

During the same EU project Open-Bio, Briassoulis et al. (2019) conducted similar field tests with the same test materials at a fish farm in Greece in a comparable temperature regime and reported complete disintegration of all samples in the benthic tests after 9 months, roughly accounting for a half-life of 140 days (estimated from the graphs provided) as compared to 738 days (PHB), 908 days (PBSe) and 1,070 days (PBSeT) in our Mediterranean benthic tests. This indicates that the trophic level of the habitat might also have a positive influence on the biodegradation activity (and rate). In our study, most of the nutrient-related parameters (*sensu* Weber et al., 2012) such as concentrations of N and P compounds were low in the three different settings. Manipulative tank experiments could be used to investigate the relationship between nutrient concentration and biodegradation rate.

The abundance of microbes and their community composition, especially in tests involving sediments, might differ strongly, e.g., dependent on factors such as grain size (Ahmerkamp et al., 2020). Different sediment types such as e.g., coarse permeable sand, fine silt, or mud due to their different permeabilities might favor strongly differing metabolic pathways, e.g., depending on the presence or absence of oxygen as an electron acceptor. Some polymers might also behave differently under oxic or anoxic conditions than others. As reported recently (Lott et al., 2020), we also observed a different disintegration performance within the same sample exposed in the HYDRA® frames (SI **Figure 1**). Due to the tightly adhering frame, the margin of the exposed plastic film (which was not accounted for in the disintegration measurements) supposedly had less

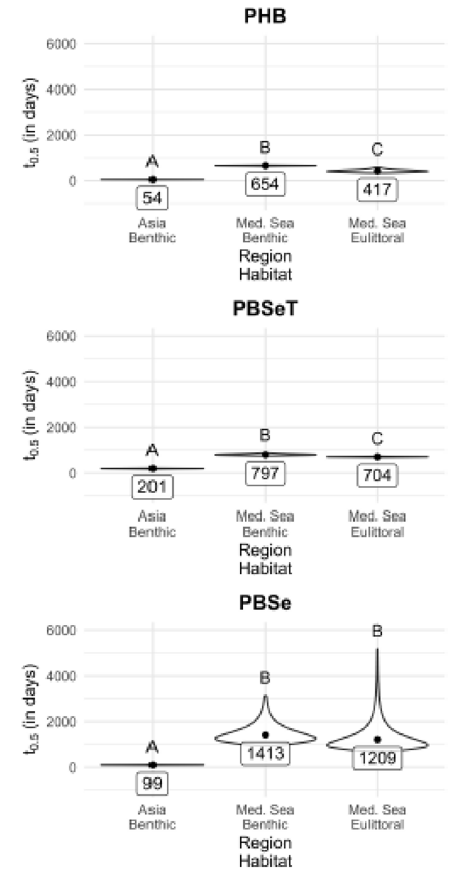

FIGURE 7 | Comparison of the disintegration half-lives $t_{0.5}$ of PHB, PBSeT, and PBSe from field experiments in tropical SE Asia and the Mediterranean Sea: Monte Carlo simulations of half-life for tested polymers in the benthic (seafloor sediment-seawater interface) in Asia and the Mediterranean Sea and in the eulittoral (beach scenario) in the Mediterranean Sea. Shown is the distribution of the centered 95 percentiles of the simulations as violin plots. The dot in the center of each violin plot represents the half-life as calculated from the model coefficient and its value is given in the box below. Letters above the violin plot represent the results of the multiple comparisons. Different letters indicate significantly different groups (i.e., Holm-adjusted p-value below $\alpha = 0.05$).

exchange with the surrounding water, and the microbes there presumably experienced hypoxic or anoxic conditions.

PHB and PBSe showed a contrasting trend in the performance in the benthic and eulittoral tests in the mesocosms experiment: PHB was disintegrating faster in the benthic than in the eulittoral and PBSe faster in the eulittoral than in the benthic. In the field tests, PHB and PBSeT disintegrated faster in the eulittoral than in the benthic, also the half-life predictions for PBSe followed this trend, but differences were not significant. In line with the results of the mesocosm tests discussed above, this is an indication that the comparison of a test material with a reference material has to be done with some caution and the application of a material as a positive control is critically scrutinized. Some well-degradable materials might perform differently under certain conditions than expected, making the desired intercalibration of test results e.g., between habitats or climate zones based on one material difficult and conclusions should be drawn with caution.

Creating Comparable Data for LC(I)A

The predictive modeling of half-lives we present here gives the opportunity to assign a numerical value for the biodegradation performance in a defined scenario (e.g., Mediterranean Sea/Pianosa Island/benthic sand) as a material property. Data provided in this manner by us and studies to come should be used for the compilation of a catalog of biodegradable materials and their properties with regard to their environmental performance that can be used for statistical comparisons of different materials in the same habitat, or one material in different environmental scenarios. These specific half-lives will also be suited to enable further mathematical modeling e.g., for environmental benefit and risk assessment and the life cycle (impact) assessment of products. Furthermore, such a catalog could help industry, public administration, and NGOs to base their decisions for or against certain materials and their application on facts.

The principle of half-life, however, is difficult to communicate and to perceive to non-specialists e.g., the general public or policy makers. The question "How long does it take?" (until a certain object is completely degraded) cannot be readily answered by the specific half-life.

Dilkes-Hoffman et al. (2019) compared the results of PHB biodegradation tests under marine conditions in a meta-analysis from eight former studies. To achieve comparability, they recalculated the data to a rate of mass loss over time per exposed surface area (Equation 3) based on the assumption that in biodegradable solids the processes causing the degradation are only happening at the surface of the object:

$$r = \Delta m \cdot A_{active}^{-1} \cdot t^{-1} \qquad (3)$$

where m is mass, A the surface area exposed, and t the time.

From these data, they also estimated the lifetime, i.e., the time needed for an *object* to completely degrade. The 95% CI of the biodegradation rates derived from all studies considered was 0.04–0.09 mg cm^{-2} d^{-1}. We applied their calculation method to our experimental results on PHB, using the volume of the films (area × thickness) and the specific gravity ρ of the material ($\rho_{PHB} = 1.3$). We obtained rates within or close to this range only for our fastest scenarios, PHB exposed in the benthic test in SE Asia (0.051 mg cm^{-2} d^{-1}), and in lab tests (0.012 mg cm^{-2} d^{-1} for eulittoral and 0.024 mg cm^{-2} d^{-1} for benthic tests). For the

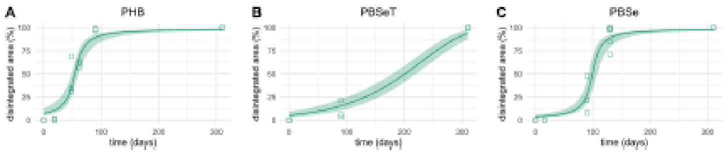

FIGURE 8 | Field experiments in tropical SE-Asia: Disintegration curves of **(A)** PHB, **(B)** PBSeT, and **(C)** PBSe exposed on the seafloor sediment-seawater interface (benthic) for almost one year (310 d). The model curve ± 95% CI (shaded area) was drawn if the slope was different from zero and positive. Squares represent raw data analyzed.

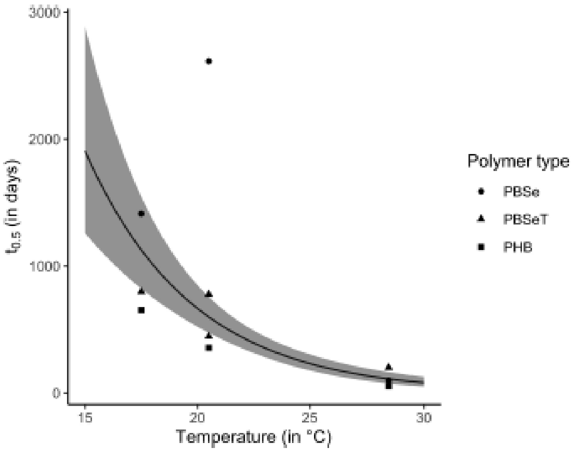

FIGURE 9 | Temperature dependence of half-life in benthic tests: half-life $t_{0.5}$ decreases exponentially with temperature. The dots are the predicted half-life values for PHB (squares), PBSeT (triangles), and PBSe (circles). The line represents an exponential model, the shaded area is the standard error.

TABLE 4 | Surface micro-bioerosion rates ($\mu m \cdot yr^{-1}$) of PHB, PBSe, and PBSeT under different marine conditions.

Polymer	Habitat	Year	Lab (20 ± 1°C)	Mesocosm (20.5 ± 1°C)	Mediterranean Sea (12–30°C)*	SE Asia (28.5 ± 0.5 °C)
PHB 85 μm	Benthic		133.8 (129.1, 139.1)	43.5 (29.0, 55.9)	23.7 (23.1, 24.5)	285.7 (259.8, 317.2)
	Eulittoral		70.0 (56.1, 79.9)	21.1 (11.8, 28.9)	37.2 (26.6, 46.7)	
	Pelagic			12.4 (6.0, 18.1)		
PBSeT 25 μm	Benthic	1	22.4 (18.1, 25.8)	5.9 (3.4, 10.6)	5.7 (5.2, 6.1)	22.7 (21.1, 24.9)
		2		10.2 (3.7, 11.7)		
	Eulittoral	1		12.5 (7.6, 25.6)	6.5 (6.3, 6.6)	
		2		31.1 (13.0, 37.7)		
	Pelagic	1		8.6 (4.2, 17.2)		
		2		20.4 (15.7, 22.0)		
PBSe 25 μm	Benthic		24.4 (24.0, 24.8)	1.7 (1.3, 2.2)	3.2 (1.5, 4.8)	46.0 (42.7, 49.1)
	Eulittoral			30.8 (27.6, 34.3)	3.8 (0.9, 6.6)	

*The range of the confidence interval CI (centered 95-percentile) is given in brackets. *temperature range (daily mean): benthic 14–20°C, eulittoral 12–30°C.*

other test scenarios, the biodegradation rates were one order of magnitude lower (**Supplementary Table 9**).

If we apply the minimum and maximum biodegradation rates derived from the results of our beach and seafloor field tests in the Mediterranean Sea and in tropical SE Asia (0.051–0.004 mg cm^{-2} d^{-1}; **Supplementary Table 9**) to estimate the lifetime of the PHB objects as in Figure 3 of Dilkes-Hoffman et al. (2019) it results in lifetimes 1.8–10 times higher, ranging from 2–20 months for a 35 μm thick shopping bag to 2.7–36 years for a PHB bottle with 800 μm thickness to 4–54 years for PHB cutlery (~1,300 μm). It has, however, to be taken into account, that the calculation of the rate by Dilkes-Hoffman et al. (2019) is based on the initial surface of the object which in reality will change during the biodegradation process. Very likely, the surface roughness will increase and the surface-to-volume ratio will become higher and thus the gross degradation of the object or its fragments will accelerate, as was also shown by Chinaglia et al. (2018). Therefore, these estimations should be taken as conservative for the environments considered. On the other hand, given the strong temperature dependence of the biodegradation rate, it can be assumed that in colder environments as the deep sea or in polar regions the lifetime will be higher.

The dependence of the (bulk) biodegradation rate on the surface-to-volume (or mass) ratio was mentioned by Modelli et al. (1999) who, in a study with another focus, compared powder (grain size 1 μm) and film of PHB (4 cm × 4 cm × 0.025 cm) in a soil biodegradation test according to ASTM (2003) and interpreted the rates as different. The authors missed to numerically address the surface-to-volume ratio in this comparison and stated that the initial rate (11 % of the 0.5 g bulk polymer in 1 day) was 90 times higher for powder deduced from the slope of the linear fits. However, if their data is re-calculated with Equation 3, the rates of 0.023 [0.056 g · d^{-1}; A = 2,400 cm^2] for powder (simplified assuming spherical particles) and 0.020 [0.132 g · 210 d^{-1}; A = 32 cm^2] for film are almost identical and the difference in the bulk rates (90 times) is well explained by the difference in surface area (75 times).

Chinaglia et al. (2018) tested also in soil (ASTM, 2003) lab experiments at 28 ± 2°C, PBSe powder of different grain sizes and found the maximum rate for 1 g of sample at 97 mg $C_{polymer}$ d^{-1} (and the total surface in dependence of grain size where half the maximum rate was reached at 1,122 cm^2). If equation 3 is applied to their data, the areal rates for PBSe particles (0.05–0.18 mg . cm^2 . d^{-1}) are about 10 to 600 times higher than our results for PBSe film (25 μm thickness) under marine conditions (**Supplementary Table 10**).

Taking into account that biodegradation of a solid object is occurring at the surface the specific half-lives modeled from results from our tests with film can be converted to erosion rates in μm per year *yr* by dividing half the film thickness *h* by the half-life $t_{0.5}$:

$$r[\mu m \cdot yr^{-1}] = (\frac{0.5\ h}{t_{0.5}}) \cdot 365 \quad (4)$$

These values are surface-independent and density-independent and can be applied to three-dimensional objects with parallel surfaces as e.g., most packaging such as bottles etc., with the only object-specific parameter to know being the material thickness.

Applying Equation 4, microbial surface erosion ("micro-bioerosion") rates derived from our experimental results range from 12.4–285.7 μm · $year^{-1}$ for PHB, 5.7–31.1 μm · $year^{-1}$ for PBSeT and 1.7–46.0 μm · $year^{-1}$ for PBSeT (see **Table 4**).

The micro-bioerosion rate in the respective habitat divided by the wall thickness in μm of an object will provide estimated lifetimes that can be used for environmental risk and life cycle assessments. Further experiments on solid objects rather than the film will be useful to validate these estimations.

The numbers presented here might also help to clarify the assumption that degradation of biodegradable plastic in the marine environment is occurring "much more slowly" and give useful input to the statement that "the degree to which "biodegradable" plastics actually biodegrade in the natural environment is subject to intense debate" (UNEP, 2015). Our data and also previous studies show that there are biodegradable plastic materials that do degrade relatively fast in the natural marine environment given their functional properties in the applications they were designed for. A stable, durable, and resistant plastic item that performs well during use is unlikely to "disappear" within a few days or weeks once lost or littered to the natural environment. This also underpins the urgency to apply all possible means to prevent any plastic material from entering the natural environment, being it biodegradable or not. Plastic lost to the environment is pollution, even if biodegradable. However, biodegradable plastics are less likely to accumulate or persist than conventional plastics.

CONCLUSION

The large spectrum of scenarios in which biodegradation tests were conducted here revealed a high variability in the rate of biodegradation of biodegradable plastics under marine conditions and confirms the impreciseness of the term "marine biodegradable." The specific half-lives differed by orders of magnitude from weeks to years and give a deep insight into the possible range of the real performance of biodegradable plastics in the open environment. The data also demystifies the assumption that in the marine environment in general the biodegradation of biodegradable plastics is slow. Although several scenarios such as the very cold habitats (deep sea, high latitudes) and areas with little or no oxygen (mainly with fine sediments) have not been touched by our study biodegradation was observed to occur to a certain extent under all conditions considered. This differentiated view together with numerically comparable rates will be useful for the estimation of the environmental persistence of biodegradable plastics in the sea in comparison to conventional plastic materials. This study also will deliver urgently sought-after base data for the assessment of benefits and risks of biodegradable plastics with regards to their environmental performance.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

Written informed consent was obtained from the individual for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

CL, MW, DM, BU, MvE, ES, AE, and MR designed experiments, conducted lab (MvE, ES), mesocosm and field experiments. AE, CL, MW, MvE, and ES analyzed data. AE performed statistical modeling. ML supervised field studies in Indonesia. CL, MW, and AE wrote the manuscript with input of all coauthors. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2021.662074/full#supplementary-material

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Sponges as bioindicators for microparticulate pollutants?☆

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ABSTRACT

Amongst other threats, the world's oceans are faced with man-made pollution, including an increasing number of microparticulate pollutants. Sponges, aquatic filter-feeding animals, are able to incorporate fine foreign particles, and thus may be a potential bioindicator for microparticulate pollutants. To address this question, 15 coral reef demosponges sampled around Bangka Island (North Sulawesi, Indonesia) were analyzed for the nature of their foreign particle content using traditional histological methods, advanced light microscopy, and Raman spectroscopy. Sampled sponges accumulated and embedded the very fine sediment fraction (<200 μm), absent in the surrounding sand, in the ectosome (outer epithelia) and spongin fibers (skeletal elements), which was confirmed by two-photon microscopy. A total of 34 different particle types were identified, of which degraded man-made products, i.e., polystyrene, particulate cotton, titanium dioxide and blue-pigmented particles, were incorporated by eight specimens at concentrations between 91 and 612 particle/g dry sponge tissue. As sponges can weigh several hundreds of grams, we conservatively extrapolate that sponges can incorporate on average 10,000 microparticulate pollutants in their tissue. The uptake of particles, however, appears independent of the material, which suggests that the fluctuation in material ratios is due to the spatial variation of surrounding microparticles. Therefore, particle-bearing sponges have a strong potential to biomonitor microparticulate pollutants, such as microplastics and other degraded industrial products.

1. Introduction

Microparticulate pollutants (later referred to as "micropollutants") are a threat to inhabitants of the world's oceans. Here, we define micropollutants as man-made substances, or products of their subsequent degradation, smaller than 5 mm in size. They are introduced into the environment and are potentially harmful to organisms, for instance as microplastics, textile fibers, and particulate toxins that leach from household and cosmetic products (Dris et al., 2016; Auta et al., 2017; Rochman 2018). Because traditional sieving techniques fail to assess the very fine particulate fraction (<200 μm) adequately (Lindeque et al., 2020), the main question driving this research is whether potential bioindicators for such anthropogenic micropollutants can be identified among marine organisms.

Sponges (Phylum Porifera) are aquatic benthic animals, which are geographically widely spread (Bell 2008). They consume mainly dissolved organic carbon (DOC), prokaryotes and ultraphytoplankton (<10 μm) by filtering fine particles from the ambient water (Yahel et al., 2006). They incorporate particles following two main paths (1) phagocytosis by choanocytes (i.e., cells that generate the water flow in the sponge body through the beating activity of their flagellum, organized in chambers): and (2) endocytosis through the exopinacoderm (i.e., external cells forming the outermost body layer) (Willenz and van de Vyver 1982; Teragawa 1986a; Hammel and Nickel 2014). Exopinacocytes may incorporate particles as big as 2 mm diameter, which deposited on the outside of the

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animal on the ectosome (Cerrano et al., 2002). Such microparticles are thought to subsequently be transported by ameboid mesohyl cells from the ectosome towards sites of skeletogenesis in non-spiculated demosponges (Teragawa 1986a). Foreign microparticles provide sponges with strength and support their growth (Teragawa 1985). They may also serve for protection (Burns and Ilan 2003) and anchorage to the substrate (Cerrano et al., 2002); Teragawa (1986b). However, mechanisms behind particle incorporation, retention and rejection in sponges are not fully understood yet. Nonetheless, we hypothesize that the fluctuation in material ratios incorporated by sponges is due to the spatial variation of surrounding microparticles; therefore, sponges may incorporate man-made micropollutants if present in their immediate environment and be viable models for biomonitoring such.

To address this issue, we carried out a combination of field and laboratory studies. The sampling of sponges was conducted in Indonesia since it is known to be a hotspot for land-based pollution in the middle of the Coral Triangle (Eriksen et al., 2014). We used histological methods, such as (nonlinear) light microscopy, as well as Raman spectroscopy for five poriferan species from Bangka Island (North Sulawesi, Indonesia) to address the following three questions: in which structure(s) do particles accumulate? what kind of particles do sponges incorporate (diversity)? do sponges have the potential to monitor microparticulate pollutants? Findings from this study contribute to fill a knowledge gap on particle incorporation by sponges, regarding accumulation areas and diversity of incorporated particles. Moreover, our study suggests that sponges are promising aquatic bioindicators for microparticulate pollutants, such as microplastics and other degraded industrial products.

2. Material and methods

2.1. Site of study and sample collection

The field work took place at Coral Eye Resort on the west coast of Bangka Island (Kabupaten Minahasa Utara, Perairan Likupang), Sulawesi Utara, Indonesia, between March 17th and April 12th, 2019, to assess the plastic contamination in marine sponges (research permit holder: Elsa Girard; SIP no.: 97/E5/E5.4/SIP/2019). The sampling area spanned approximately 7 km^2 and specimens were sampled at two different locations: Coral Eye house reef South and North from the jetty (Supplementary material Fig. S1; Tab. S1). Non-lethal sponge samples (n = 15) of fragments of maximum 8 cm^3 tissue were taken from five abundant sponge species (3 specimens collected per sponge species, later referred to as "triplicate") known to naturally incorporate foreign microparticles. The sample collection was done at water depth between 1 and 3 m below the lowest tide using a stainless-steel diving knife. Collected samples were preserved in two aliquots: 96% ethanol for DNA barcoding and 4% formaldehyde for histology and spectroscopy. An *in situ* picture of each specimen was taken, showing the macro-morphological features of the species. Molecular, histological and Raman spectroscopy analyses described below were performed on all 15 sponge samples.

In addition, one sand sample from Coral Eye Resort was collected for comparison in the intertidal zone near the jetty (later referred to as "beach sand") using a polyethylene terephthalate (PET) plastic bottle. A random subsample of the sand was transferred into a 1.5 mL Eppendorf microtube (Eppendorf AG, Hamburg) using a metal spatula. The beach sand was prepared for Raman spectroscopy the same way as the sponge samples were (see below), going through bleaching, washing and filtration steps. Microparticles (<200 µm) were not extracted from the beach sand sample. Due to the small sand sample size (n = 1), it may potentially introduce a control bias.

2.2. Species identification

At the Molecular Geobiology and Paleobiology laboratory of the Department of Earth & Environmental Sciences, Paleontology & Geobiology, LMU Munich, the 15 sponge specimens collected from five different species were identified and confirmed to the genus using integrative taxonomy (Wörheide and Erpenbeck 2007; Voigt and Wörheide 2016). The DNA was extracted from the sponge samples using a DNA extraction kit (NucleoSpin® Tissue, Macherey-Nagel GmbH & Co. KG). DNA barcoding was conducted using a fragment of the 28S ribosomal DNA, a region amplified using universal primers via polymerase chain reaction (PCR) (Supplementary material Tab. S2). The DNA was sequenced with BigDyeTerminator v3.1. Sanger Sequencing was conducted at the Genomic Sequencing Unit of the LMU Munich, using an ABI 3730 (Erpenbeck et al., 2017).

Forward and reverse sequences were assembled and edited using CodonCode Aligner v3.7.1.2 (www.codoncode.com). Sequences of poriferan origins were identified with BLAST® for nucleotides using the NCBI database (https://blast.ncbi.nlm.nih.gov) and combined to the 28S sponge data set (Erpenbeck et al., 2016) available at the Sponge Genetree Server (www.spongegenetrees.org). The data set was largely reduced to concentrate on the important clades, by selecting only the nearby taxa (taxonomically classified) with the least genetic distance to the samples. Alignments were performed in MAFFT v7.427 (https://mafft.cbrc.jp/alignment/software/), default settings. Subsequently, a phylogenetic tree was calculated for 28S sequences in Seaview v4.6.3 (Gouy et al., 2010) under PhyML Generalized Time-Reversible model with the invariable site and gamma shape settings obtained via jmodeltest 2.1.10 v20160303 (Darriba et al., 2012), and included 100 bootstrap replicates (Guindon et al., 2010). Final barcoding data (alignments and trees) is stored on GitHub repository (https://github.com/PalMuc/PlasticsSponge).

2.3. Histological analysis

All 15 sponge samples that were initially fixed with 4% formaldehyde overnight were gradually dehydrated with ethanol at the Coral Eye Resort laboratory (Indonesia). At the laboratory in Munich, samples were prepared for thin sectioning in LR-white medium to preserve the original position of foreign particles within the tissue. Sections with a thickness ranging between 50 and 400 µm were cut depending on the specimen morphology, using a saw microtome (Leica SP1600). Sections were mounted on microscope slides using Eukitt Quick-hardening mounting medium. The histological analysis was conducted using a microscope Leica DMLB (Type 020–519.502 LB30 T BZ:00, Leica Mikroskopie & Systeme GmbH Wetzlar) with a mounted digital camera. Images of the same field of views were taken under brightfield and (cross-) polarized light illumination. The polarized light fields allowed a better recognition of the foreign particles in the sponge, embedded in the organic tissue. Field of views of the ectosome, mesohyl, skeletal structures and aquiferous system (i.e., canals and choanocyte chambers) were recorded for each specimen. The histological analysis also enabled the description of the sponge main morphological micro-features.

In addition to the assessment of particle accumulation areas, relative particle abundance and size were analyzed with ImageJ v1.52K (Schindelin et al., 2012). All tissue images utilized for the analysis were taken under the same settings (100 µm thin section, equal luminosity and magnification) to ensure comparability of the data. To measure the particle's relative abundance, images were translated into grayscale (8-bit) and the mean light intensity of ten random square areas (264.52 µm side length) were measured per structure and per sample. The mean light intensity is a numerical value generated by the software that allows for a comparison between areas and samples with an arbitrary unit (AU). Unpolarized light illumination was chosen for keratose sponges, because the spongin tissue from the skeletal fibers has a high transmission with little scattering comparable to the particles. On the contrary, (cross) polarized light illumination was used for heterosclermorphs, to observe particles in these heavily spiculated specimens with high organic matter content. Images taken with polarized light were treated in a second step by inverting the gray scale in order to have dark particles on a pale background, similarly to the images taken with unpolarized light. Therefore, the lower the intensity value, the darker the area and the more particles are present. The particle size was also assessed and categorized with ImageJ: small (most particles <50 µm diameter), large (most particles > 50 µm diameter) or mix (presence of small and large particles at a similar fraction). The diameter corresponds to the longest axis of the particle. The data gathered from the particle distribution, abundance and size was analyzed in R v3.3.3 (R Core Team 2017). Primary data and R scripts are available on GitHub repository (https://github.com/PalMuc/PlasticsSponge).

2.4. Particle distribution with two-photon excitation

Histological sections of sponge tissue were analyzed by two-photon excitation (TPE) 3D imaging, to highlight the contrast between the highly fluorescent organic tissue from the sponges in opposition to the non-fluorescent mineral particles incorporated by the sponge. Samples were evaluated after histological preparation. For two-photon imaging, fresh sections of 170 µm thickness were prepared without staining and mounted on microscope slides using Eukitt Quick-hardening mounting medium. Brightfield pictures of the scanned area were taken before the experiment followed by a 3D scan of the specimen. Each 2D image had a range of 190 µm, an acquisition time of 180 s and a step size of 380 nm. The 3D step size between the 2D image planes and the total number of planes was chosen with respect to the object of interest and ranged from 10 to 21 planes with 0.5–3 µm steps.

Imaging was carried out on a confocal scanning microscope (TE 300; Nikon) with mounted bright-field illumination and camera. The two-photon excitation source was a fiber-based, frequency-double erbium laser (FemtoFiber dichro bioMP, Toptica Photonics) running at 774 nm. The laser power was 10 mW. The laser light was coupled into the microscope via a low pass dichroic mirror (HC BS 749 SP; AHF Analysetechnik) that separates laser excitation and fluorescence emission. Scanning of the sample in 3D was achieved by using a xyz piezo stage (BIO3.200; PiezoConcept). The laser excitation was focused onto the sample with a 60x (water) 1.20-NA plan apochromat objective (Plan APO VC 60× 1.2 NA, Nikon). The emission was collected by the same objective and passed afterwards through a bandpass filter (SP600; AHF). The emission was recorded on an APD detector (Count Blue; Laser Components) and its photons stream registered using a TCSPC card (TH260 pico dual; PicoQuant GmbH). The experiment was controlled using a home-written program written in C#. The confocal data was extracted and evaluated afterwards by PAM (Schrimpf et al., 2018) and ImageJ2 (Schindelin et al., 2012).

2.5. Raman spectroscopy

Raman spectroscopy was performed on all 15 sponge samples and the beach sand, and the analyses permitted the identification and quantification of particles on a filter and *in situ*, i.e., from thin sections (30–50 µm thick). As preparation for Raman measurements, all sponge samples were firstly subsampled, dried and weighed. The subsamples weighed between 2.2 and 11 mg. The sponge tissue and the beach sand was digested in 1.5 mL household bleach over 2–3 days, with a one-time bleach renewal. All samples were then washed with MilliQ water five times in a row. Particles left were filtered through a nitrocellulose membrane (Whatman™, 1 µm mesh size) with the aid of a vacuum pump. One hundred particles were randomly measured per sample (referred to as "random" search pattern). Furthermore, a maximum of ten additional particles per sample were measured on purpose depending on differences in color, shape and texture to assess the diversity of incorporated particles in lower abundance (referred to as "target" search pattern). In addition, the spectrum of white and a red sclerites of *Tubipora musica* (sample number GW1858, obtained from an individual grown in an aquarium at the Molecular Geobiology and Paleobiology laboratory) was measured to compare its red pigment signal to that of the red particles present in sponges.

Raman spectra were taken on a confocal Raman microscope (HORIBA JOBIN YVON XploRa ONE micro Raman spectrometer) at the SNSB–Mineralogical State Collection Munich. The Raman spectrometer used is equipped with a Raman edge longpass filter, a Peltier cooled CCD detector and three different lasers working at 532 nm (green), 638 nm (red) and 785 nm (near IR). Here, 532 nm excitation was used to perform the measurements, with a long working distance (LWD) objective magnification 100× (Olympus, series LMPlanFL N), resulting in a 0.9 µm laser spot size on the sample surface. The power required for high-quality spectra varied between 10% and 100% (i.e., respectively 0.879 mW and 8.73 mW ± 0.1 on the sample surface) depending on the type and size of measured particles. The diameter of pin-hole and the slit width were set to 300 and 100 µm, respectively. Each acquisition included two accumulations with an integration time of 8 s over a spectral range of 50–2000 cm^{-1} (ca. 35 s per measurement). Resulting Raman spectra were analyzed using LabSpec Spectroscopy Suite software v5.93.20, compiled in a table, visualized in R v3.3.3, manually sorted in Adobe Illustrator CS3, and compared with available spectra from RRUFF database (see: http://rruff.info/index.php) and published work (e.g., Zięba-Palus and Michalska (2014)). The statistical ANOSIM test (Analysis of Similarity) was performed in R v3.3.3, using 999 permutations in the vegan package (Oksanen et al., 2017) to assess the similarity in foreign particle assemblage composition between species, subclasses and sampling locations. Raman spectra and analysis scripts written in R used for the analysis are available on GitHub repository (https://github.com/PalMuc/PlasticsSponge).

2.6. Precautions against contaminants

To avoid contamination of the samples, latex gloves, glassware, cotton towel and dust-free wipers (Kimtech Science) were used when manipulating all 15 sponge samples at all times. All open manipulations done in Molecular Geobiology and Paleobiology laboratory at LMU, i.e., dissection and filtration of the samples, were conducted under a clean bench (BDK, Luft-und Reinraumtechnik GmbH). Eppendorf safe-lock tubes 1.5 mL (polypropylene) were used to centrifuge the subsamples during tissue digestion and subsequent washing steps. Consequently, a negative sample was included, undergoing the same steps as all samples from tissue digestion to particle filtration. Due to the airborne exposure of the samples in the field at Coral Eye Resort laboratory and the presence of fibers on the negative filter, all resulting fibers in this study were regarded as contaminants and therefore not taken into account. Only microparticles, excluding microfibers, were analyzed.

3. Results

Five particle-bearing species were particularly abundant around Bangka Island (Indonesia), and were sampled three times to generate the triplicates (n = 15). In order to determine the accumulation areas of foreign particles in coral reef sponges, the samples were taxonomically classified to the genus level into 5 clades: *Carteriospongia*, *Ircinia* I, *Ircinia* II, Tethyid I and Tethyid II (Supplementary material Fig. S2; Tab. S3) and histologically analyzed. Subsequently, the samples were examined with Raman spectroscopy to assess the diversity of incorporated particles.

3.1. Particle distribution

Thin sections provided an overview of the main structures and the distribution of particles within sponge bodies. Incorporated particles were located and identified with polarized light microscopy using TPE 3D imaging and Raman spectroscopy. No particles were found inside choanocyte chambers; only particles surrounding choanocyte chambers were observed in both Tethyid species. Therefore, no further statistical analysis was conducted on choanocyte chambers.

Foreign particles were observed by (nonlinear) light microscopy in the aquiferous system, the mesohyl, the ectosome and the fibrous skeleton, depending on the species (Figs. 1 and 2). Two-photon microscopy clearly confirmed that the incorporated particles were completely embedded in the surrounding tissue (Fig. 2, Supplementary material Fig. S3). All specimens incorporated particles in the mesohyl and the ectosome. Moreover, 73% of the specimens, independently of the skeletal material, had some particles in the aquiferous system; the clades *Ircinia* I did not contain particles in their canals. All specimens of the subclass Keratosa incorporated particles in their skeletal spongin fibers (e.g., Fig. 2D), whereas heteroscleromorphs did not because they have siliceous spicules instead of fibers as skeletal structures (Fig. 1).

Across all specimens, particles embedded in the mesohyl (e.g., Fig. 2A) were in lower abundance (the higher the light intensity, less dense the particle cover), in comparison to the density of particles accumulated in spongin fibers and/or the ectosome (Fig. 1). Moreover, thorough microscopy analyses revealed a majority of small particles (<50 µm) present in the mesohyl/aquiferous system and accumulated in the ectosome (Figs. 1 and 2). Larger particles (>50 µm) were observed in spongin primary fibers of keratose sponges (Figs. 1 and 2). Only specimens from the clade *Ircinia* I incorporated large particles in all three structures. The size of uptaken particles between *Ircinia* species differed although they belong to the same genus. In fact, the clade *Ircinia* II reflected *Carteriospongia*'s particle size pattern. Measured particles on the filters varied in size, with a diameter ranging from 5 µm to approximately 200 µm, which are equivalent in size to the particles measured *in situ* (Fig. 2). The size of the particle may therefore indicate in which structure particles might have been incorporated in relation to Fig. 1, for example, larger particles in Keratosa are more likely to accumulate in the fiber network than the mesohyl (Figs. 1 and 2). The fine fraction (<200 µm) was absent from the beach sand sample, where only coarse particles (>500 µm diameter) were observed.

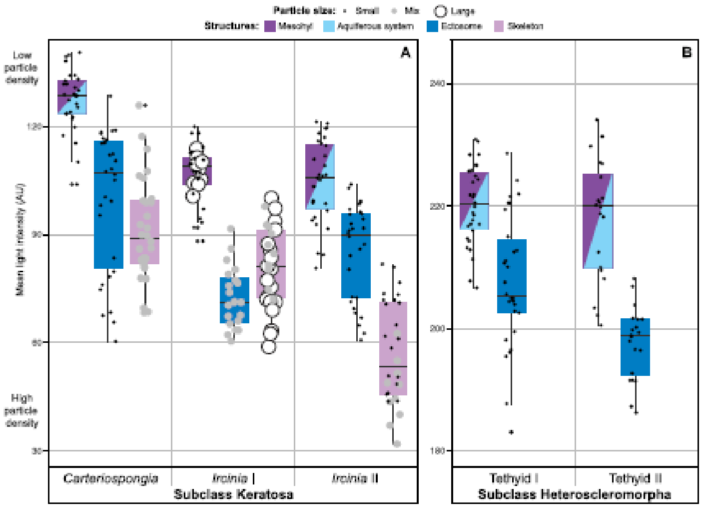

Fig. 1. Particle distribution amongst sampled sponges and their abundance in tissue structures as derived from brightfield imaging. A) Subclass Keratosa, B) subclass Heteroscleromorpha. The lower the intensity, i.e., absorption of the specimen body, the higher the number of particles in the structure; the aquiferous system was not differentiated from the mesohyl in cases where particles were present in the aquiferous system. Particle size is represented by the size and color of the dots (i.e., black small dots for a majority of particles < 50 µm, white large dots for a majority of particles > 50 µm and gray medium dots for a more or less equal presence of small and large particles). Color code: skeleton in lila, aquiferous system in cyan, mesohyl in purple, ectosome in blue. The box size corresponds to the 25th (bottom) and 75th (top) percentile of the data (known as the interquartile range) and the middle line shows the median (50th percentile). The error bars correspond to the smallest and largest value within 1.5 times the interquartile range below and above the 25th and 75th percentile, respectively. The mean light intensity (y-axis) is given in an arbitrary unit (AU). Note: relative intensity within the same subclass can be compared, however not between the subclasses as the scale used was different. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

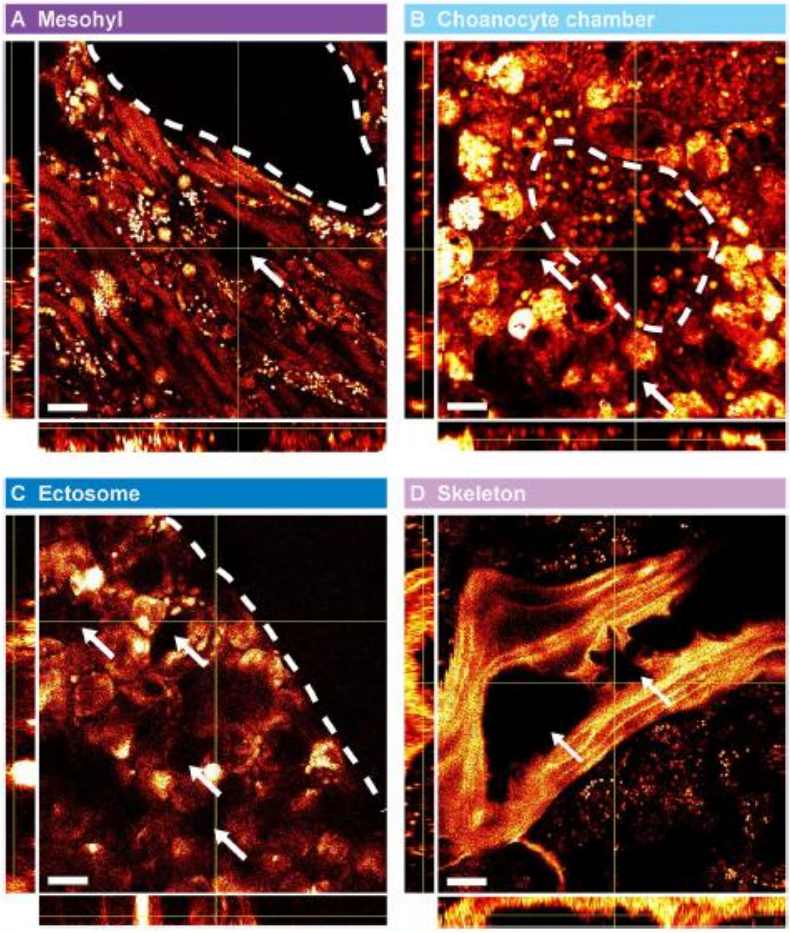

Fig. 2. Two-photon images of three-dimensional sponge tissue sections with embedded foreign particles. The auto-fluorescence of the organic tissue material serves as imaging contrast compared to inorganic particles that are non-fluorescent. XZ and YZ projections through the 3D image stack are depicted aside of each XY projection (brightfield images are shown in Supplementary material Fig. S3). Exogenous particles are embedded in the tissue (some examples are marked with white arrows) and are found A) in the mesohyl of *Ircinia* sp. (the canal is circled with a dashed line), B) surrounding the choanocyte chamber of Tethyid sp. (circled with a dashed line), C) at the ectosome of Tethyid sp. (the dashed line separates the outermost part of the sponge tissue), and D) in spongin fibers of *Carteriospongia* sp.. Z-scan ranges are 18 μm and scale bars are 20 μm.

3.2. *Particle diversity*

A total of 1686 particles were measured on 15 filters (between 103 and 110 particles per filter). Across all measured particles on the filters, 34 different spectra were identified, of which 22 were associated to a single material or pigment (aragonite, calcite, amorphous calcite, quartz, β-quartz, anatase, feldspar, graphite, magnetite, mackinawite, ferrosilite, cotunnite, hematite, riebeckite derivative, polystyrene, particulate cotton, carbon, *Argopecten irradians* shell, red biomineralization type I and II, blue pigment type I and II) (Fig. 3, Supplementary material Tab. S4). The 12 remaining spectra are polymineralic particles and were interpreted as a mixture of two different materials (e.g., aragonite + quartz). Our results also show a high variability and diversity of the scarce incorporated compounds between the different species, including particles derived from anthropogenic products (Supplementary material Tab. S5, S6).

3.2.1. *Inorganic compounds*

As illustrated in Fig. 3, calcite and aragonite (i.e., $CaCO_3$) showed similar vibrational bands around 150, 705 and 1085 cm^{-1}, but calcite had a band at ca. 280 cm^{-1}, whereas aragonite had one at ca.

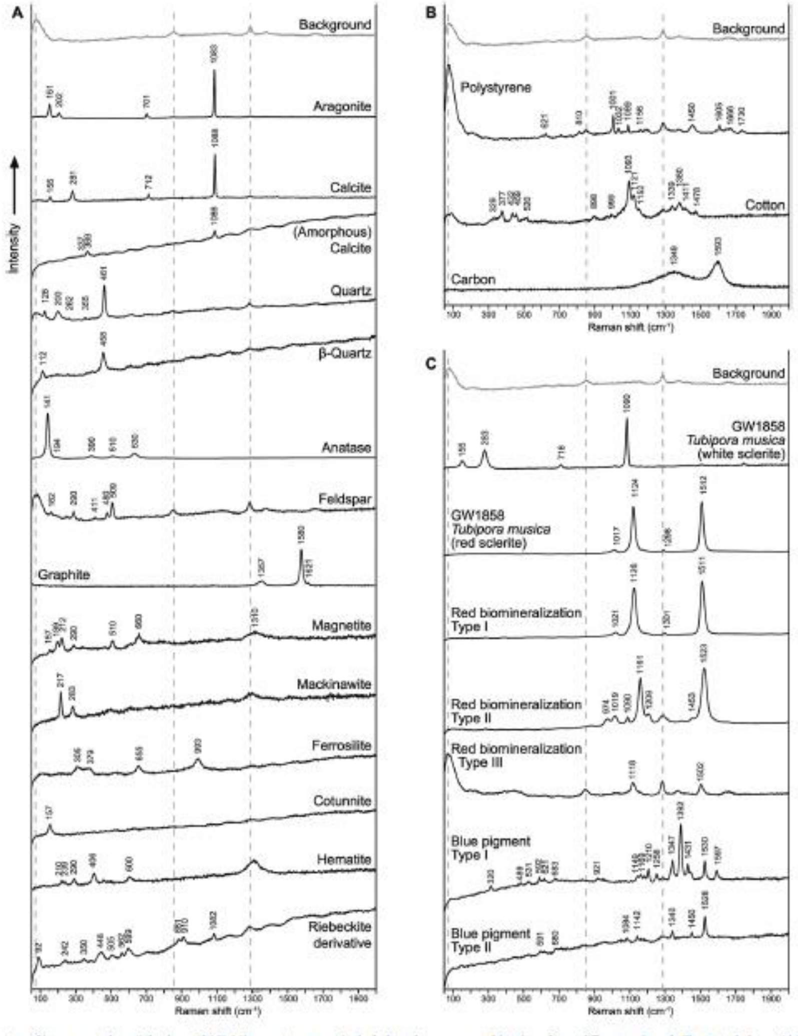

Fig. 3. Raman spectra of incorporated particles (n = 1686). Mix spectra are not included, as they are a combination of two different minerals illustrated above. A) inorganic spectra. B) organic spectra. C) spectra associated with pigments. Red biomineralization spectra are compared to GW1858 (octocoral *Tubipora musica* red and white sclerites). Numbers over the signatures indicate the highest point of each vibrational band. Dotted lines indicate bands corresponding to the background.

205 cm^{-1} due to their different crystallographic structures. Quartz was characterized with a vibrational band at 460 cm^{-1}, related to the Si–O–Si bond. Carbonate phosphate showed two weak vibrational bands at ca. 960 cm^{-1} (phosphate; PO_4^{3-}) and 1075 cm^{-1} (carbonate; CO_3^{2-}). Feldspar was distinguished by three vibrational bands: ca. 290, 480 and 510 cm^{-1} (silica; Si), and anatase by one main band at ca. 140 cm^{-1}. The D-band (ca. 1350 cm^{-1}) and G-band (ca. 1580 cm^{-1}) are indicative for carbon-based materials, such as carbon, graphene and graphite. Given the band shape and ratio between both lines (Roscher et al., 2019), we identified the compounds as carbon and graphite (Fig. 3).

3.2.2. Organic compounds

Polystyrene was measured for two particles during a random search pattern. Particles, such as particulate cotton and blue colored particles, were found during a target search pattern

(Supplementary material Tab. S5). Some of these materials potentially come from man-made products, which is discussed in detail below. One specimen of *Carteriospongia* sp. (4.6 mg dry weight) and one of *Ircinia* I (6.3 mg dry weight) contained polystyrene at a concentration of 0.217 and 0.159 particle/mg, respectively. Four specimens from the Genus *Iricnia* (4.8, 4.9, 6.3 and 6.5 mg dry weight, respectively) were found with particulate cotton at concentrations between 0.154 and 0.612 particle/mg.

3.2.3. Pigmented compounds

The Raman signature of a white and a red sclerite of *Tubipora musica* (GW1858) showed that the red pigment signal generally (peaks at 1326 and 1511 cm^{-1}) covers all vibrational bands of calcite (ca. 280 and 1085 cm^{-1}). However, this red pigment (type I), found also in red aragonitic particles (e.g., red type I + aragonite), did not overtake the vibrational bands of aragonite (ca. 150 and 1085 cm^{-1}), ubiquitous across all samples. A second and third red pigments were also detected with Raman spectroscopy, showing peaks at 1161 and 1523 cm^{-1} and at 1118 and 1502 cm^{-1}, respectively. Red pigment type III is slightly shifted compared to the type I and II (Fig. 3). Finally, blue-pigmented particles were observed on the filter of two specimens from the clade Tethyid I (11.0 and 8.5 mg dry weight, respectively) at a concentration of 0.091 (type I) and 0.118 (type II) particle/mg.

3.3. Mineral ratios

Aragonitic and calcitic particles were identified in all observed structures. Tethyid clades did not only incorporate minerals, but also a considerable amount of particulate organic matter (Fig. 2C and D). Keratosa specimens incorporated on average 68% aragonite and 25% calcite, whereas Heteroscleromorpha specimens had 59% and 30%, respectively (Fig. 4). The aragonite-calcite median ratio of Tethyid I was 1.875, Tethyid II 2.462, *Cartegiospongia* 2.680, *Ircinia* I 2.310 and *Ircinia* II 2.783. Although all specimens had a higher aragonite-calcite ratio on average than that of the beach sand (ratio = 1.735), no species had significantly different particle ratio compared to one another and to the sand sample (ANOSIM: $P = 0.067$) as well as between the subclasses (ANOSIM: $P = 0.392$) based on the Analysis of Similarity (Fig. 5C and D). Specimens were also compared on their aragonite-calcite ratio according to the location they were collected, i.e., Coral Eye house reef South or north. The Analysis of Similarity also indicates that the particle ratio did not significantly vary between the sampling sites (ANOSIM: $P = 0.620$) (Fig. 5E).

Other than aragonite and calcite, < 2% of quartz was measured across all clades, but it was not present in the beach sand. However, 4% of the coarse grains in the beach sand sample was feldspar, which was also identified in *Carteriospongia* and both Tethyid clades. Carbonate phosphate and titanium oxide (anatase) were respectively measured on *Ircinia* II and Tethyid II filters (Supplementary material Tab. S5). Anatase was found at concentrations of 0.208 and 0.345 particle/mg. Most abundant polymineralic particles observed across the samples were quartz + aragonite and quartz + anatase, although both of them found in low concentrations (Supplementary material Tab. S5). The Analysis of Similarity suggests that the species have no preference on the material to be incorporated, because the species did not have significantly different material assemblage composition (ANOSIM: $P > 0.05$).

4. Discussion

In this study, 15 demosponges (3 of *Carteriospongia* sp., 6 of *Ircinia* spp. and 6 of Tethyid spp.) were histologically analyzed and characterized with respect to their foreign particle content with light microscopy and Raman spectroscopy. The particle density was higher in the ectosome and spongin fibers of keratose sponges than

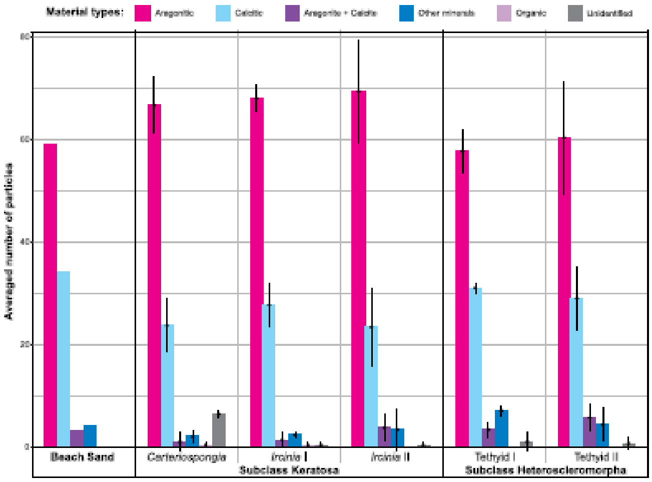

Fig. 4. Diversity of materials among sampled sponges. Particle diversity from resulting Raman measurements of 100 randomly selected particles per sample. Each species accounts for 3 samples, and particle counts were averaged per clade (pink: aragonitic; cyan: calcitic; purple: aragonite + calcite; blue: other minerals; lila: organic; gray: unidentified). Error bars represent the standard deviations in number of particles compared to the mean between the specimens of the same species. The category "Unidentified" results from low quality spectra, which could not be associated with any known material. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

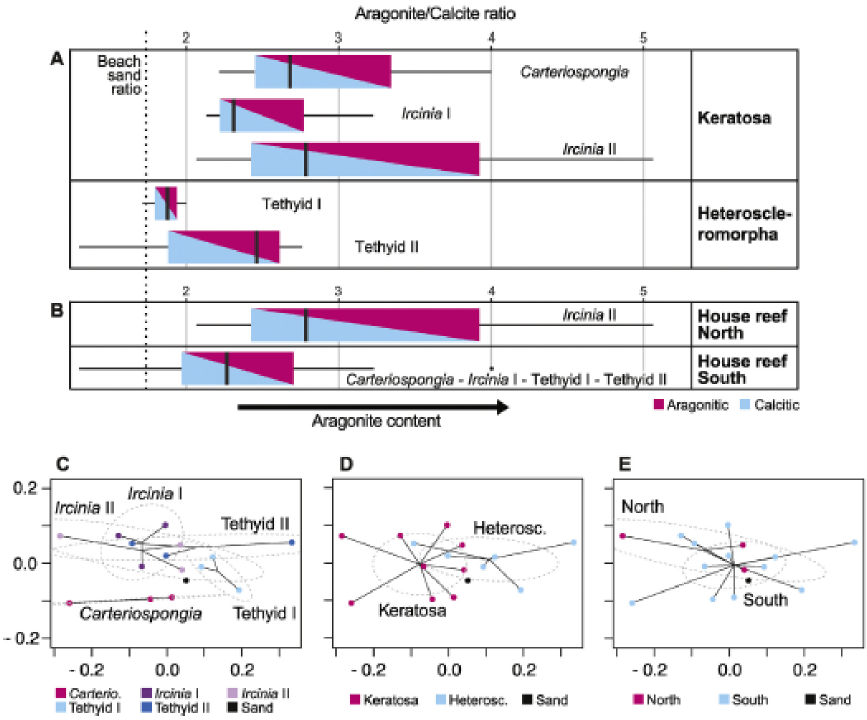

Fig. 5. Aragonite to calcite ratio A) at the species level and B) according to the sampling site. The beach sand sample ratio (1.735) is indicated with the dotted vertical line. The box size corresponds to the 25th (bottom) and 75th (top) percentile of the data (known as the interquartile range) and the middle line shows the median (50th percentile). The error bars correspond to the smallest and largest value within 1.5 times the interquartile range below and above the 25th and 75th percentile, respectively. Non-metric multidimensional scaling (NMDS) plots C) at the species level, D) at the subclass level and E) according to the sampling site, displaying the differences between the foreign particle assemblage composition. Dashed gray ellipses represent the 99% confidence interval. Note: the Analysis of Similarity indicates no significant differences between the samples at all three comparison levels (ANOSIM: $P > 0.05$).

in the mesohyl, and no particles were observed in choanocyte chambers. Embedded foreign particles were of larger size in keratose spongin fibers, whereas generally smaller than 50 µm in the mesohyl and the ectosome, as confirmed with TPE analysis. A wide range of different particles were present in low percentages on the filters (<3%), such as feldspar, quartz, carbonate phosphate, red pigments and composites. Moreover, several particles are most certainly of anthropogenic origin, i.e., particulate cotton, titanium dioxide, plastic and blue pigments, at densities between 0.091 and 0.612 particle/mg dry sponge tissue. No species preferentially incorporated particles of particular material type.

4.1. Incorporation of foreign particles

The capture and retention of foreign particles are common practice amongst sponges, especially noticeable within members of the subclass Keratosa, for instance species of the genus *Dysidea* embed particles in their spongin fibers (Willenz and van de Vyver 1982; Teragawa 1986a; Cerrano et al., 2007). The pathway most likely used to incorporate coarse particles in the core of spongin fibers is the endocytosis by exopinacocytes (Willenz and van de Vyver 1982; Teragawa 1986a). The diffusion of foreign particles through the ectosome towards the mesohyl in keratose specimens from Bangka Island suggests a particle transfer from the superficial region of the sponge towards the inner one. These findings indicate that the mesohyl serves as a transit zone for particle transport in keratose demosponges. Similar pathways are likely used by heteroscleromorph demosponges; however, patterns observed in our study show differences between accumulation areas. Indeed, Tethyid clades present a thick and dense ectosome hosting organic and inorganic particles of size equal to or smaller than 50 µm diameter. Similar particles also aggregate around choanocyte chambers, which indicates that particles are incorporated via both processes, i.e., captured by the exopinacocytes and absorbed or phagocytized by choanocytes. Consequently, sponges tend to select more voluminous particles (>50 µm) to support their skeleton in keratose demosponges and to retain smaller particles (<50 µm) in the ectosome in spiculated demosponges (Teragawa 1986b; Cerrano et al., 2007). Based on these findings, microparticulate pollutants are incorporated by sponges either in skeletal fibers or the ectosome, or both depending on the particle size and sponge species.

Other possible effects arise as sponges also incorporate micropollutants, for instance toxins associated with these microparticles can leach, impacting sponge development and pumping capacity (Hill et al., 2002). Likewise, microbial pathogens hitchhiking on, for example, microplastics may negatively affect sponges (Taylor et al., 2007), both of which will have a direct impact on the ecosystem they inhabit. Keratose demosponges may also use particulate micropollutants to build their skeleton and support their growth, creating temporary sinks or an expressway to enter the marine food chain through spongivores. On a more positive note, sponges likely host degrading bacteria able to remineralize certain micropollutants (Lee et al., 2001), taking the sponge loop theory to the next level.

4.2. Origins of micropollutants

A wide range of different materials was observed in sponges from Bangka Island. On the one hand, they are autochthonous and reflect geological formations, e.g., quartz and feldspar (Carlile et al., 1990; Kavalieris et al., 1992), and reef assemblages, e.g., tunicates and reef-building corals (Yamano et al., 2000; Bergamonti et al., 2011; Łukowiak 2012), of the surroundings. Indeed, slow weathering and erosion processes generate the detachment of particles that compose, together with the reef's coral sand production, most of today's Bangka Island sand. On the other hand, they are allochthonous and foreign to the natural environment, such as titanium dioxide, particulate cotton, blue-pigmented particles and microplastics.

4.2.1. Titanium dioxide

Titanium dioxide (TiO_2), i.e., anatase, brookite and rutile, can naturally accumulate in the sand subsequent to weathering of the titanium-bearing mineral ilmenite by underground water (Premaratne and Rowson 2003). At the same time, anatase is also used as a white pigment, i.e., PW6 (titanium white), in automotive paints (Zięba-Palus and Michalska 2014), pharmaceutical coatings (Alexander 2008), thermoplastic resin (Kitamura and Mitsuuchi 1996) and archeological paints (Middleton et al., 2005). That being said, none of the Raman vibrational bands measured in our study directly correspond to a white pigment. Nanoparticulate anatase, together with rutile, is also extensively used for its chemical properties and UVB protective behavior in sunscreens (Yue et al., 1997; Jaroenworaluck et al., 2006; Serpone et al., 2007). Hence, anatase particles found in sponges from Coral Eye house reef might as well come from the degradation of anthropogenic anatase-containing products, such as sunscreens, and not only from natural sources.

4.2.2. Blue pigments

Particles of highly similar blue color to the human eye were incorporated in two specimens of the clade Tethyid I. The blue pigments, however, showed two different Raman signatures. The main vibrational bands were also measured by Zięba-Palus and Michalska (2014) who identified those as from blue pigments used in car paints. The blue pigment Type I is most probably a mix between the pigment PV23 (dioxazine violet) and PB15 (phthalocyanine 15) and the blue pigment Type II PB15, according to the findings of Zięba-Palus and Michalska (2014). These synthetic organic pigments might also be used in marine coating or recreational painting (Bouchard et al., 2009). Because the Raman vibrational bands of the pigments overwrite that of its polymer composition, it is not possible to identify the nature of the particle. However, the pigment PB15 was previously recorded as a dye associated with microplastics isolated from the soft tissue of bivalves (van Cauwenberghe and Janssen 2014) and intertidal textile fibers (Girard et al., 2020).

4.2.3. Textiles and microplastics

High tides and winds bring large quantities of marine debris, including plastics and textiles, on to the shores of Bangka Island (EB Girard, personal observation; Giebel (2018) unpublished report). The litter lands on beaches, where the highest degradation rate of plastic has been reported (Andrady 2017). Coral Eye Resort volunteers clean the beach daily, however this is not done systematically all around the island yet, nor on proximal coast lines (EB Girard, personal observation). Not surprisingly then, eight microparticles were herein identified as particulate cotton ($n = 6$) or polystyrene ($n = 2$) in all sampled keratose species. Cotton fabric has also been reported to be the most observed fabric in environmental dust, as fibers in the atmosphere, but also in the intertidal zone (Dris et al., 2016, 2017; Girard et al., 2020). Nevertheless, some of these particles may also originate from the cloth made of cotton that was used to dry glass dishes to avoid plastic contamination of the samples. Polystyrene is one of the three most abundant microplastic materials reported at sea, together with polyethylene and polypropylene (Andrady 2017; Auta et al., 2017). Our results are further supported by the findings of Ling et al. (2017), who estimated that the concentration of microplastic particles in the sediment reaches up to 0.4 particle/mL in the southern coasts of Australia. The authors noticed a consistent microplastic concentration across 42 sampling sites. Moreover, microparticles of plastic were at highest concentration in a size range ca. 60–400 µm (Ling et al., 2017), which is concordant with the particle size incorporated by the sponge exopinacoderm. Because sponges can pump several decades to hundreds of liters per day (Leys et al., 2011) and microparticles deposit on their ectosome, Bangka specimens indeed incorporated microplastics.

4.3. Sponges as bioindicators

Sponges are potentially ideal local bioindicators because they are sessile animals and widely distributed across all aquatic habitats. In fact, the families of sponges occurring around Bangka island have previously been recorded from various other localities in Indonesia (van Soest 1989, 1990; Cerrano et al., 2002, 2006; Bell and Smith, 2004; de Voogd et al., 2006, 2009; 2009; de Voogd and Cleary, 2008; Becking et al., 2013; Calcinai et al., 2017a, b) (Supplementary material Fig. S4).

Our study confirms that sponges are efficient sediment traps, recording the diversity of the matter in the ambient water as they are able to register this diversity to the finest grain (<200 µm), otherwise difficult to recall solely based on sand samples (Janßen et al., 2017). Sponges have also been recognized as bioindicators for environmental stress (Carballo et al., 1996), water quality (Mahaut et al., 2013), and multiple pollutants, e.g., by heavy metals (Selvin et al., 2009; Venkateswara Rao et al., 2009) and polychlorobiphenyl (Perez et al., 2003). Furthermore, a recent study identified sponges as a good monitor to record more efficiently DNA of surrounding vertebrates than robotic samplers for environmental DNA (eDNA) (Mariani et al., 2019). Such biological monitors also provide information over a time window, whereas traditional net tows represent only a single point in time (Lindeque et al., 2020). Furthermore, in sediment traps, the fine fraction is washed away by currents, leading to biases in the actual particle diversity present in the sediment at a given location (Janßen et al., 2017).

4.3.1. Extrapolation to realistic micropollutant concentrations

Based on our results, sampled sponges did not preferentially incorporate particles of specific materials, which suggests that fluctuation in material ratios is due to the spatial variation of surrounding microparticles. At a concentration higher than 0.1 particle/mg of dry sponge tissue, here from keratose demosponges (*Carteriospongia* sp. and *Ircinia* spp.) weighing ca. 6 mg (dry weight), we extrapolate that at least 10,000 microplastic particles can be incorporated by sponges weighing more than 100 g (dry weight). Similar approximations can derive from the results regarding abundance of blue-pigmented particles, particulate cotton and titanium dioxides in the spiculated demosponge Tethyid species. Because sponges can weigh several hundreds of grams (Reiswig, 1971; McMurray et al., 2008), they have the potential to accumulate non-negligible amounts of micropollutants. Sponges from museum collections have also been recently surveyed positively for fibrous microplastics (Modica et al., 2020). A larger screening of associated particles in sponge tissue, combined with carbonate dissolution, is likely to reveal more microplastics and other particles derived from anthropogenic products.

5. Conclusion

This study narrows the knowledge gap on particle incorporation processes and provides a first assessment on the particle diversity in sponges. Indeed, 34 particles of different nature were identified using Raman spectroscopy including micropollutants (i.e., polystyrene, particulate cotton, blue-pigmented particles, titanium dioxide). As sponges incorporate these micropollutants from their surroundings, a sample of sponge tissue may provide a unique estimate of the local micro-pollution available to the immediate fauna. Based on current knowledge and findings from this study, we conclude that particle-bearing sponges have the very promising potential to biomonitor micropollutants, such as particles putatively originating from anthropogenic products (e.g., microplastics). Whether sponges can disintegrate these micropollutants to the atomic or molecular level, and the effect this has on the immediately neighboring fauna is matter of future research.

Credit author statement

Elsa B. Girard, Conceptualization, Methodology, Validation, Investigation, Writing - original draft, Writing - review & editing, Visualization, Formal analysis. Arian Fuchs, Methodology, Validation, Investigation, Writing - original draft, Visualization, Formal analysis. Melanie Kaliwoda, Writing - original draft, Supervision, Resources. Markus Lasut, Project administration, Resources. Evelyn Ploetz, Writing - original draft, Writing - review & editing, Validation, Visualization, Supervision, Project administration, Resources, Funding acquisition. Wolfgang W. Schmahl, Resources. Gert Wörheide, Conceptualization, Methodology, Validation, Writing - original draft, Writing - review & editing, Supervision, Project administration, Resources, Funding acquisition

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2020.115851.

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Jenis, komposisi, dan kepadatan sampah laut di Teluk Manado, Sulawesi Utara, pada musim hujan

Type, composition, and density of marine litter in Manado Bay during rainy season

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Abstract: During rainy season, a various type of litter can enter the ocean through rivers. This is a significant contributor to the amount of marine litter in the waters. In order to access the type, composition, and density of the litter during rainy season, this study was conducted in Manado Bay, North Sulawesi. The observation was done on the litter stranded on the beach, and they were classified into two different size groups, macro (>2,5 cm)- and meso (0,5-2,5 cm)-sizes. Malalayang Beach and Bailang Beach were chosen for the location of the study. Litter type, composition, and density was evaluated according to National Marine Litter Monitoring Guide. The result showed that there were 7 types of macro-size and 6 types of meso-size marine litter in Malalayang Beach and it was dominated by glass and ceramic for both sizes. In Bailang Beach, 9 types of macro-size and 7 of meso-size were found, and it was dominated by plastics. It can be concluded that various type of marine litter present in Manado Bay, both macro- and meso- sizes, during the rainy season. The highest composition was the glass and ceramics type. However, the highest density was the plastic type.

Keywords: marine litter; waste management; Manado Bay; North Sulawesi; Indonesia

Abstrak: Pada musim hujan, berbagai jenis sampah dari daratan masuk ke perairan pantai melalui sungai. Hal ini merupakan penyumbang signifikan bagi jumlah sampah laut di perairan. Untuk menilai jenis bahan, komposisi, dan kepadatan sampah laut pada musim hujan, penelitian ini dilakukan di Teluk Manado, Sulawesi Bagian Utara. Pengamatan dilakukan terhadap sampah laut yang terdampar di pantai (beach litter), berukuran makro (> 2,5 cm) dan *meso* (0,5-2,5 cm), di dua lokasi, yaitu Pantai Malalayang dan Pantai Bailang. Sampah laut dievaluasi menggunakan Pedoman Nasional tentang Pemantauan Sampah Pantai. Hasil penelitian menunjukkan, sampah laut jenis plastik, kaca & keramik, busa plastik, kertas & kardus, logam, karet, kayu, kain, dan bahan lainnya, baik berukuran makro maupun *meso* ditemukan di perairan. Di Pantai Bailang, komposisi sampah laut berukuran makro dan *meso* didominasi oleh jenis bahan plastik; tetapi, di Pantai Malalayang didominasi oleh jenis kaca & keramik. Demikian juga untuk kepadatan sampah laut di Pantai Bailang, jenis bahan plastik mendominasi, baik sampah berukuran makro maupun *meso*. Sedangkan di Pantai Malalayang, jenis kaca & keramik mendominasi kepadatan sampah laut pada semua ukuran. Selanjutnya, dapat disimpulkan, pada musim hujan, berbagai jenis bahan sampah laut berada di Teluk Manado, baik berukuran makro maupun *meso*. Komposisi terbesar untuk ukuran makro dan *meso* ialah jenis bahan kaca & keramik. Namun, kepadatan tertinggi untuk ukuran makro dan *meso* ialah sampah jenis bahan plastik.

Kata-kata kunci: sampah laut; pengelolaan sampah; teluk manado; Sulawesi Utara; Indonesia

PENDAHULUAN

Sampah laut didefinisikan sebagai limbah padat yang masuk ke lingkungan perairan laut yang berasal dari aktivitas manusia (Gall and Thompson, 2015). Sampah ini masuk ke lingkungan laut melalui saluran drainase kota, sungai, dan/atau dibawa oleh pengunjung ke pantai (Derraik, 2002). Keberadaannya memberikan dampak bagi eko-sistem perairan, aspek ekonomi, dan sosial (Lippiatt, et al., 2013). Sampah plastik merupakan salah satu jenis sampah laut yang paling sering ditemukan di lingkungan, khususnya di daerah pantai. Menurut Jambeck et al. (2015), Indonesia merupakan negara penyumbang sampah plastik ke laut terbesar kedua di dunia. Pada tahun 2010, Indonesia menyumbang sekitar 3,2 juta ton sampah plastik.

Kemajuan pesat di berbagai bidang pembangunan untuk meningkatkan kesejahteraan masyarakat, nampaknya diiringi oleh kemunduran kemampuan sumber daya alam sebagai penyangga kehidupan yang menghasilkan produk sampingan, salah satu diantaranya adalah sampah (Syafi'i et al., 2001). Hal ini terjadi di Kota Manado di mana, menurut BPS (2018), peningkatan wisatawan di Kota Manado, baik dalam dan luar negeri, mencapai 1.739.729 orang pada tahun 2017. Hal ini tentu bisa menjadi ancaman tersendiri terhadap Teluk Manado di mana sampah akan terus meningkat sehingga memberikan dampak negatif terhadap penduduk kota terlebih khusus kondisi lingkungan perairan laut (Lasut et al., 2018).

Menyadari akan dampak yang dapat ditimbulkan oleh sampah laut, secara nasional, Pemerintah Indonesia bertindak dengan mengeluarkan regulasi melalui Peraturan Presiden (Perpres), Nomor 83, Tahun 2018, tentang Penanganan Sampah Laut. Peraturan ini bertujuan untuk menetapkan strategi, program, dan kegiatan dalam bentuk rencana aksi nasional penanganan sampah laut dari tahun 2018-2025. Selain itu, peraturan ini juga merekomendasi pemerintah daerah agar membuat kebijakan dalam hal percepatan penanganan sampah laut.

Bertolak dari situasi dan kondisi tersebut di atas, dalam upaya pengelolaan sampah laut di Kota Manado, maka penelitian ini dilakukan, yang bertujuan untuk menilai jenis bahan, komposisi, dan kepadatan sampah laut di Teluk Manado, khususnya pada musim penghujan (pada bulan Januari). Sampah laut yang diamati yaitu sampah yang terdampar di pantai (*beach litter*) berukuran makro (> 2,5 cm) dan *meso* (0,5-2,5 cm).

MATERIAL DAN METODE

Waktu dan Lokasi Pengambilan Sampel

Pengambilan sampel sampah laut dilakukan pada tanggal 24-25 Januari 2020. Waktu pengambilan sampel masuk dalam periode musim hujan di mana rerata curah hujan selama bulan tersebut sebesar 331,1 mm. Jumlah rerata curah hujan di atas 150 mm dikategorikan sebagai musim hujan (BMKG Manado, unpublished data).

Lokasi pengambilan sampel ditentukan berdasarkan kriteria yang direkomendasikan oleh KLHK (2017), antara lain, yaitu pantai berpasir atau berkerikil, tidak terdapat pemecah ombak atau bangunan lainnya, dan kemiringan landai-moderat. Dua lokasi di Teluk Manado, yang dianggap masuk dalam kriteria tersebut, ditentukan sebagai lokasi pengambilan sampel dalam penelitian ini, yaitu: 1) Pantai Malalayang (01°27'36" LU & 124°48'15" BT) dan Pantai Bailang (01°31'32" LU & 124°50'32" BT). Kedua lokasi ini telah ditetapkan sebagai Lokasi Pemantauan Sampah Laut di Kota Manado oleh Kementerian Lingkungan Hidup dan Kehutanan (KLHK) sejak tahun 2017 (Lasut, 2017).

Pengambilan sampel dilakukan menggunakan panduan KLHK (2017). Daerah pengamatan, yang memiliki panjang 100 m, dibagi menjadi 5 lajur tegak lurus dengan garis pantai dengan jarak 20 m. Pada setiap lajur ditentukan 2 bagian, yaitu satu bagian ke arah laut dan bagian lainnya ke arah darat. Pada kedua bagian tersebut akan ditempatkan kuadran berukuran 5x5 m; penempatannya dilakukan secara sembarang (haphazardly). Pada masing-masing kuadran tersebut dibuat sub-kuadran berukuran 1x1 m; berjumlah sebanyak 25 sub-kuadran. Lima sub-kuadran dipilih secara acak (random; menggunakan Daftar Bilangan Acak) dari 25 sub-kuadran tersebut. Kemudian, sub-kuadran (5 buah; berukuran 1x1 m), yang telah dipilih, dibagi menjadi 4 bagian (diberi label sebagai A, B, C, D) berukuran 0,5 x 0,5 m.

Sampel sampah laut dikumpulkan dari permukaan substrat (pasir atau kerikil) dengan cara mengupasnya sampai pada kedalaman 5-10 cm dari permukaan. Sampah berukuran makro dikumpulkan pada semua sub-kuadran 1x1 m yang telah dipilih dengan cara menyaring menggunakan saringan berukuran 2,5 cm. Sementara itu, sampel berukuran *meso* diambil di semua Bagian A pada semua sub-kuadran 1x1 m dengan cara menyaring menggunakan saringan 0,5 cm dan 2,5 cm secara bersama-sama (diletakkan secara bersusun) di mana sampah yang terkumpul pada saringan 0,5 cm yang dikumpulkan.

Semua sampel disimpan secara terpisah di dalam wadah plastik yang telah diberi label untuk diidentifikasi, kelompokkan (klasifikasi), dan secara berturut-turut dihitung dan ditimbang untuk mendapatkan jumlah dan berat sampel per jenis. Identifikasi dan pengelompokkan (klasifikasi) sampel menggunakan panduan KLHK (2017). Penimbangan sampel dilakukan menggunakan timbangan analitik (ketelitian 0,1 g).

Analisis Data

Data (jumlah dan berat) sampel per jenis dianalisis menggunakan panduan KLHK (2017) untuk menghitung komposisi dan kepadatan sampah, untuk masing-masing ukuran sampah (makro dan *meso*), sebagai berikut:

a) Komposisi sampah ditentukan dengan menghitung persentase (%) berat sampah per jenis per keseluruhan sampah dalam daerah pengamatan dengan rumus:
Komposisi (%) = $\frac{x}{\sum_{i=1}^{n} Xi} \times 100\%$, di mana: x = berat sampah per jenis.

b) Kepadatan sampah dihitung dari jumlah sampah per jenis per m^2 dengan rumus
K = $\frac{Jenis}{panjang\ x\ lebar}$, di mana: panjang dan lebar diukur dalam meter.

HASIL

Jenis Bahan Sampah Laut

Tabel 1 dan 2, berturut-turut, menampilkan jenis sampah laut (marine litter) yang terdampar di Pantai Malalayang dan Pantai Bailang. Di Pantai Malalayang, ditemukan 7 jenis bahan sampah laut berukuran makro, yang diklasifikasi ke dalam 24 macam; sedangkan yang berukuran *meso*, ditemukan 6 jenis, yang diklasifikasikan ke dalam 15 macam. Di Pantai Bailang, ditemukan 9 jenis bahan berukuran makro, yang diklasifikasi ke dalam 32 macam; dan, 7 jenis berukuran *meso*, yang diklasifikasi ke dalam 22 macam.

Tabel 1. Jenis bahan sampah laut (*marine litter*) terdampar di Pantai Malalayang, Teluk Manado

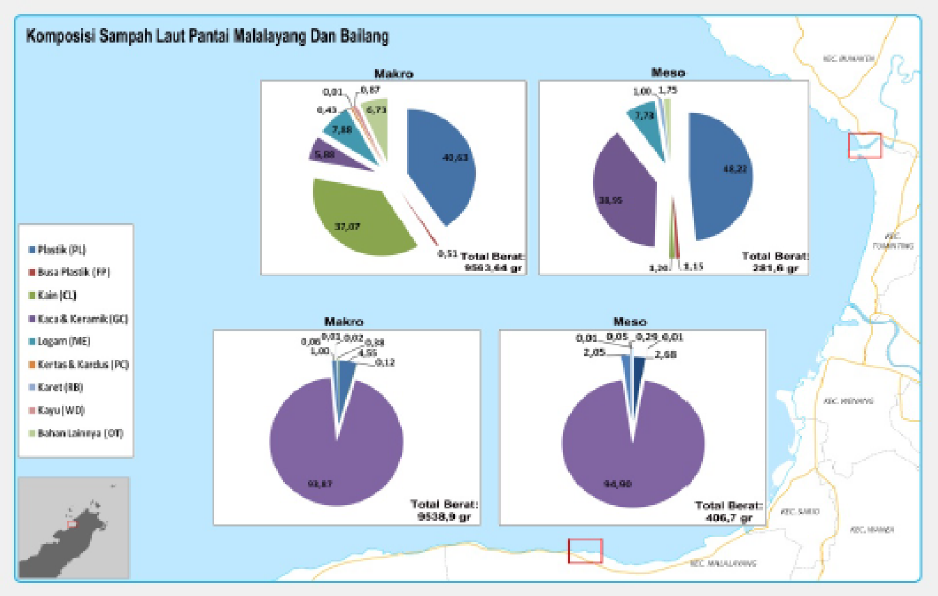
Jenis Bahan	Kode	Klasifikasi	Makro	*Meso*
Kain	CL06	Kain lainnya	✓	-
Busa plastik	FP01	Busa spons	-	✓
Kaca & keramik	GC01	Material bangunan	✓	✓
	GC02	Botol kaca	✓	-
	GC07	Pecahan kaca dan keramik	✓	✓
Logam	ME03	Kaleng Aluminium	✓	-
	ME08	Serpihan logam	✓	✓
	ME09	Kawat	✓	✓
	ME10	Logam lainnya	-	✓
Bahan Lainnya	OT02	Alat kebersihan (popok & pembalut)	✓	-
	OT03	Peralatan elektronik	✓	✓
	OT05	Bahan lainnya (pulpen)	✓	-
Kertas & kardus	PC05	Kertas lainnya	✓	✓
Plastik	PL01	Tutup botol plastik	✓	✓
	PL02	Botol < 2 L	✓	-
	PL03	Jerigen	✓	-
	PL04	Sedotan/sendok plastik	✓	-
	PL05	Paket peralatan minuman	✓	-
	PL06	Paket peralatan makanan	✓	-
	PL07	Kantong plastik	✓	-
	PL11	Puntung rorok	-	✓
	PL18	Senar Monofilament	✓	✓
	PL22	Serpihan fiberglass	✓	✓
	PL24	Plastik lainnya	✓	✓
Karet	RB02	Sendal	-	✓
	RB08	Karet lainnya	✓	✓
Kayu	WD05	Batang korek kayu	✓	-
	WD06	Kayu lainnya	✓	-

Tabel 2. Jenis bahan sampah laut (*marine litter*) terdampar di Pantai Bailang, Teluk Manado

Jenis Bahan	Kode	Klasifikasi	Makro	*Meso*
Kertas	CL01	Pakaian & Sepatu	✓	✓
Busa spons	FP01	Busa spons	✓	✓
Kaca & keramik	GC01	Material bangunan	✓	-
	GC02	Botol kaca	✓	-
	GC04	Lampu	-	✓
	GC07	Pecahan kaca dan keramik	✓	✓
Logam	ME01	Peralatan makanan besi	✓	-
	ME03	Kaleng aluminium	✓	-
	ME04	Kaleng lainnya	✓	-
	ME06	Bungkus foil	✓	✓
	ME08	Serpihan logam	-	✓
	ME09	Kawat	-	✓
	ME10	Logam lainnya (paku)	✓	-
Bahan lainnya	OT02	Popok	✓	-
	OT03	Peralatan elektronik	✓	✓
Kertas & kardus	PC02	Kardus	✓	-
	PC03	Bungkus rokok	✓	-
Plastik	PL01	Tutup botol plastik	✓	✓
	PL02	Botol plastik < 2L	✓	✓
	PL03	Jerigen/botol > 2 L	✓	-
	PL04	Sedotan/sendok	✓	✓
	PL05	Paket peralatan minuman	✓	✓
	PL06	Paket peralatan makanan	✓	✓
	PL07	Kantong plastik	✓	-
	PL08	Mainan plastik	✓	✓
	PL10	Korek rokok	✓	✓
	PL11	Puntung dan filter rokok	-	✓
	PL12	Jarum suntik	✓	-
	PL16	Terpal	✓	✓
	PL17	Peralatan memancing	✓	-
	PL19	Tali tambang	✓	✓
	PL22	Serpihan fiberglass	✓	✓
	PL24	Plastik lainnya	✓	✓
Karet	RB05	Lembaran karet	-	✓
	RB08	Karet lainnya	✓	✓
Kayu	WD02	Kayu rumpon	✓	-
	WD06	Kayu lainnya	✓	-

omposisi Sampah Laut

Gambar 1 menampilkan komposisi sampah ut di masing-masing lokasi penelitian. Di lokasi ıntai Bailang, untuk ukuran makro, didominasi eh sampah jenis bahan plastik (kode PL; ımposisi sebesar 40,63 %; berat sebesar 3.885,24 dan diikuti oleh jenis bahan kain (CL; 37,07 %; 3.544,93 g), logam (ME; 7,88 %; 753,15 g), dan bahan lainnya (OT; 6,73 %; 643,82 g). Sedangkan untuk ukuran *meso*, juga didominasi oleh sampah jenis bahan plastik (PL; 48,22 %; 135,8 g) dan diikuti oleh kaca & keramik (GC; 38,95 %; 109,7 g), logam (ME; 7,73 %; 21,8 g), dan bahan lainnya (OT; 1,75 %; g).



Gambar 1. Komposisi Sampah Laut di Teluk Manado, Sulawesi Utara

Di lokasi Pantai Malalayang, komposisi sampah laut ukuran makro yang dominan ialah bahan jenis kaca & keramik (GC; 93,87 %; 8.954,46 g) dan diikuti jenis bahan plastik (PL; 4,55 %; 433,72 g), logam (ME; 1 %; 95,44 g), dan bahan lainnya (OT; 0,38 %; 36,22 g). Sama halnya dengan ukuran makro, komposisi sampah laut ukuran *meso* didominasi oleh jenis bahan kaca & keramik (GC; 94,90 %; 385,9 g) dan diikuti oleh jenis plastik (PL; 2,68 %; 10,9 g), logam (ME; 2,05 %; 8,3 g), dan karet (RB; 0,29 %; 1,2 g).

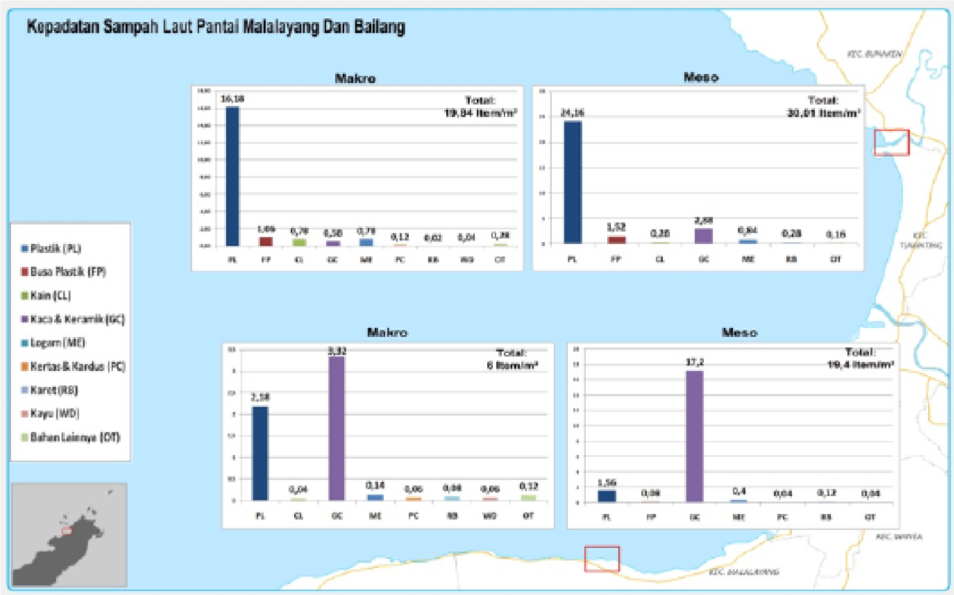
Kepadatan Sampah Laut

Di lokasi Pantai Bailang, kepadatan sampah laut ukuran makro didominasi oleh jenis bahan plastik (kode PL; sebanyak 16,18 potongan/m²) dan diikuti oleh jenis busa plastik (FP; 1,06 potongan/m²), dan kain (CL) dan logam (ME) dengan kepadatan yang sama (0,78 potongan/m²). Sedangkan untuk ukuran *meso*, sampah jenis bahan plastik (PL; 24,16 potongan/m²) mendominasi dan diikuti oleh jenis bahan kaca & keramik (GC; 2,88 potongan/m²), busa plastik (FP; 1,52 potongan/m²), dan logam (ME; 0,84 potongan/m²) (Gambar 2).

Berbeda dengan lokasi sebelumnya, kepadatan sampah laut ukuran makro di Pantai Malalayang didominasi oleh jenis bahan kaca & keramik (GC; 3,32 potongan/m²) dan diikuti oleh jenis plastik (PL; 2,18 potongan/m²), logam (ME; 0,14 potongan/m²), dan bahan lainnya (OT; 0,12 potongan/m²). Demikian juga untuk kepadatan sampah laut ukuran *meso* di mana didominasi oleh jenis bahan kaca & keramik (GC; 17,2 potongan/m²). Dominasi sampah jenis kaca & keramik tersebut diikuti oleh jenis bahan plastik (PL; 1,56 potongan/m²), logam (ME; 0,4 potongan/m²), dan karet (RB; 0,12 item/m²).

PEMBAHASAN

Curah hujan dan angin yang bertiup dari daratan dapat mempengaruhi kelimpahan sampah di laut (Chesire & Adler, 2009). Djamaluddin (2019) menjelaskan, bahwa curah hujan di Teluk Manado sangat besar dipengaruhi oleh pola angin. Angin Barat Laut, yang bertiup dari Laut Cina Selatan, membawa kelembaban yang tinggi selama Bulan September hingga April. Pada Bulan November, angin tersebut tiba di Pulau Sulawesi bagian Utara lewat Laut Sulawesi dan menuju Pantai Barat Sulawesi Selatan sekitar akhir Bulan November atau awal Bulan Desember. Hal inilah diduga, yang menyebabkan curah hujan tinggi (331,1 mm) pada bulan Januari, saat pengambilan sampel dilakukan,



Gambar 2. Kepadatan Sampah Laut di Teluk Manado, Sulawesi Utara, Indonesia

Bangun et al. (2019) mengamati, sampah jenis bahan plastik mendominasi di Pantai Tasik Ria, Kabupaten Minahasa, dengan komposisi mencapai 58,15 %. Tetapi, untuk berat sampah didominasi oleh jenis kaca. Pantai Tasik Ria merupakan pantai bersebelahan dengan lokasi penelitian Pantai Malalayang. Namun, jenis sampah kaca & keramik (93,87 %) yang mendominasi di Pantai Malalayang (Gbr. 1); sampah jenis ini juga memiliki kepadatan tertinggi (3,32 potongan/m^2) (Gbr. 2).

Thiel et al. (2013) menjelaskan, bahwa sampah laut jenis bahan plastik dapat mengapung dalam waktu yang lama dan dapat hancur menjadi partikel yang lebih kecil. Selanjutnya, proses sedimentasi pantai berperan penting, setelah sampah plastik terdampar, kemudian akan terkubur pada sedimen; bahkan dalam jangka waktu yang panjang dapat terkubur lebih dalam lagi. Lebih lanjut dijelaskan oleh peneliti tersebut, bahwa pada pantai berbatu, gelombang laut dapat menghancurkan sampah menjadi berkeping-keping dan terperangkap pada sedimen. Hal inilah diduga yang terjadi di lokasi Pantai Malalayang di mana sampah jenis kaca & keramik mendominasi sampah yang ada (Gbr. 1 dan 2).

Menurut Pelamatti et al. (2019), sungai memainkan peran yang signifikan dalam menyumbang sampah ke laut. Selama periode musim hujan, seiring dengan debit air sungai yang meningkat, sampah dari daratan akan lebih banyak terakumulasi di daerah pantai yang berdekatan dengan sungai. Seperti yang terjadi di Teluk Banderas, Meksiko, di mana pantai yang ada didominasi oleh sampah laut jenis plastik. Terzi & Seyhan (2017) juga melaporkan hal yang sama, bahwa sungai memiliki peran dalam menyumbang sampah ke laut. Pantai Bagian Tenggara di Laut Hitam, Turki, didominasi oleh sampah jenis plastik hingga mencapai lebih dari 70 %. Hal ini diduga yang terjadi di Pantai Bailang dalam penelitian ini di mana sampah jenis plastik mendominasi.

Dalam hubungan antara tipe pantai dan proses yang terjadi terhadap sampah laut, Thiel et al. (2013) menjelaskan, bahwa terdapat perbedaan proses untuk setiap tipe pantai. Pada pantai tipe berbatu, sampah yang tiba di pantai tersebut akan dihancurkan atau digiling, layaknya pabrik penggiling, oleh gelombang atau arus pantai. Seperti yang terjadi di Pantai Malalayang, yang merupakan tipe pantai berbatu. Akibatnya, sampah laut ukuran *meso*, seperti kaca & keramik (GC), sangat domin-an ditemukan. Dalam hal dampaknya bagi organisme laut, hal ini sangat berbahaya, karena sampah laut yang berukuran *meso* (0,5-2,5 cm) dapat tertelan oleh ikan, burung laut, dan mamalia laut. Efek tertelannya sampah laut ke dalam tubuh organisme laut dapat menjadi transpor polutan organik seperti dichlorodiphenyl trichloroethane (DDT) dan polychlorinated biphenyls (PCB) ke dalam tubuh organisme; bahkan dapat mengakibatkan mortalitas bagi organisme tersebut (Rosevelt et al., 2013).

KESIMPULAN

Dari penelitian ini dapat disimpulkan, bahwa pada musim hujan, jenis bahan sampah laut di Teluk Manado, yang ditemukan terdampar di pantai (*marine litter*), meliputi jenis plastik, kaca & keramik, busa plastik, kertas & kardus, logam, karet, kayu, kain, dan bahan lainnya, baik berukuran makro maupun *meso*. Komposisi terbesar untuk ukuran makro dan *meso* ialah jenis bahan kaca & keramik. Namun, kepadatan tertinggi untuk ukuran makro dan *meso* ialah sampah jenis bahan plastik.

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RESEARCH ARTICLE

Field and mesocosm methods to test biodegradable plastic film under marine conditions

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Abstract

The pollution of the natural environment, especially the world's oceans, with conventional plastic is of major concern. Biodegradable plastics are an emerging market bringing along potential chances and risks. The fate of these materials in the environment and their possible effects on organisms and ecosystems has rarely been studied systematically and is not well understood. For the marine environment, reliable field test methods and standards for assessing and certifying biodegradation to bridge laboratory respirometric data are lacking. In this work we present newly developed field tests to assess the performance of (biodegradable) plastics under natural marine conditions. These methods were successfully applied and validated in three coastal habitats (eulittoral, benthic and pelagic) and two climate zones (Mediterranean Sea and tropical Southeast Asia). Additionally, a stand-alone mesocosm test system which integrated all three habitats in one technical system at 400-L scale independent from running seawater is presented as a methodological bridge. Films of polyhydroxyalkanoate copolymer (PHA) and low density polyethylene (LD-PE) were used to validate the tests. While LD-PE remained intact, PHA disintegrated to a varying degree depending on the habitat and the climate zone. Together with the existing laboratory standard test methods, the field and mesocosm test systems presented in this work provide a 3-tier testing scheme for the reliable assessment of the biodegradation of (biodegradable) plastic in the marine environment. This toolset of tests can be adapted to other aquatic ecosystems.

Introduction

Biodegradable plastic materials are being introduced into the market with a growing share in recent years [1], with common uses including food packaging, very lightweight bags and agricultural applications. The possible environmental benefit of biodegradable plastics is dependent on the application. For example, certified soil-biodegradable mulch films [2] are utilized to substitute conventional plastic polyethylene films, especially for those applications in which

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complete recollection of the film is not possible. After use, certified soil-biodegradable mulch films are plowed into the soil and biodegraded by microbes, avoiding the accumulation of non-degradable plastic fragments in the fields. It is fundamental to keep in mind that biodegradation is not only the visual disappearance or loss of weight of the material, but its remineralization to CO_2 (and/or CH_4 under anoxic conditions) and water, and the conversion to biomass by the metabolic action of microbes. Furthermore, biodegradable substitute materials are opted for as a mitigation against marine plastic pollution (e.g. [3]).The proof of environmental biodegradability, i.e. beyond controlled lab test conditions, is crucial for a polymer to be considered as a sustainable alternative to non-biodegradable materials in a specific environment. However, while there exist certification schemes for industrial compostability (e.g., based on standards [4–6]) or soil biodegradability [2], at the time this work was started, there was a lack of standards and methods for assessing marine biodegradability. It is well recognized that positive experimental results on biodegradation of plastics in one environment (e.g. in industrial compost) do not automatically imply comparable or sufficient biodegradation rates of the same material in another system (e.g. in the marine environment) [7, 8].

The knowledge on the biodegradation of biodegradable polymers in freshwater and marine environments is still very limited and experimental data vary strongly. Hence, there is a clear need (and also clear international political call, e.g. The European Green Deal, 12.11.2019 [9]) for reliable environmentally relevant standardized test methodologies to produce comparative and scientifically valid results and for the verification of claims based on sound knowledge rather than assumptions [10]. Data from such tests will help to assess environmental benefits and potential risks and will allow for their comprehensive life cycle assessment.

This need was also emphasized in a recent review [11] which identified three major knowledge gaps regarding biodegradability standards for carrier bags in aquatic environments: the relation of laboratory-based data to patterns of biodegradability within open aquatic environments, the absence of biodegradability standards and test methods for unmanaged aquatic environments and a lack of wider laboratory- and field-based research into polymer degradation within several environments. All three aspects were addressed methodologically in our study.

Biodegradation tests on biodegradable polymers in open aquatic environments have been performed since the onset of industrial development of biodegradable polymers in the 1980s, e.g. of PHA bottles in a Swiss lake [12], films of different starch blends in a river and a pond of Illinois, USA [13], films and plates of different PHAs at the sea shore of Jogashima, Japan [14] and PHB and PHBV test sticks ('dog bones') in freshwater ponds, a canal and a seawater harbor in Belgium [15]. Later, marine in-situ tests on several materials in different habitats (surface, open water, sand, mud, mangrove, reef, deep sea) were performed in the Caribbean [16], NW-Atlantic [17], NE Atlantic [18, 19], the Baltic Sea [20–25], NW Pacific [26], NE Pacific [27] SE Asia [28], the Mediterranean Sea [29] and in freshwater [25, 30–33]. Lately, the focus of field research also included microbiological [19, 34] and ecotoxicological aspects [35, 36], and the assessment of the biodegradation of marketed products rather than pure polymers [37–41]. Although field tests have been conducted for several decades the variety of methodologies and experimental conditions render the comparison of results difficult.

In-situ experimentation under sometimes harsh marine conditions is challenging and involves several risks including theft, sabotage, conflict with other activities like fisheries and boating, and natural forces such as strong currents and wave action. Loss of samples by anthropogenic impact or natural forces (e.g. [29, 38, 40, 42]) could substantially jeopardize the outcome of experiments. Also, most studies have only tested in one habitat (e.g. [38]) or were too short-termed (e.g. [39]) to produce reliable results on the full biodegradation of a certain material under marine conditions. Many studies also lack the application of a positive control to assess the general microbial activity under the given test conditions and the potential of the microbial community to biodegrade organic materials within the experimentation time at all (e.g. [41]).

The main goal of this study, partly conducted during the EU project Open-Bio [43–45], was to develop robust, reliable *in-situ* test systems to assess the performance of biodegradable plastic materials under natural marine conditions that: (a) withstand natural forces for extended times of exposure, (b) allow for testing in different marine habitats without the loss of samples and (c) provide samples ideally deteriorated by mere biological processes rather than physical destruction. Additionally, the aim was to create a basis for an internationally recognized standard, e.g. EN or ISO, which recently was successfully achieved [46].

When we started this work, standard test methods for *in-situ* testing of plastic materials only existed for the sea surface [47]. For laboratory testing several standards addressing different habitat scenarios are available (water: [48]; sediment-water interface: [49, 50]; beach sand: [51, 52]) and more are under development for the water column [53, 54]. Mesocosm (or tank) tests under controlled conditions simulate an environment which better approximates nature than is possible in small-scale laboratory tests. Thus, mesocosm tests can play an important role as a methodological bridge between field and lab tests (3-tier approach), allowing better understanding of the fundamental parameters controlling biodegradation. Mesocosms of various sizes have been used for the assessment of the performance and environmental effects of conventional and biodegradable plastic under aquatic conditions, either in flow-through systems [e.g. 17, 55–63] or closed-circuit tanks [e.g. 25, 64–72] with a large variety of technical properties and environmental conditions. Currently, only one standard test exists [73] which describes the degradation of plastic materials in mesocosm tests; however it requires the supply of running seawater. For this reason, we developed a stand-alone mesocosm system independent of the direct access to seawater, combining the simulation of three coastal marine habitats in a compact unit.

The marine environment is extremely complex and different compartments cover a large variety of conditions. Therefore, a set of tests is required to address this variety. Considering that 80% of plastic pollution originates from land [74], we focused mainly on the coastal regions. We chose three scenarios that cover different ecological aspects: the eulittoral, where plastic is washed to the beach and eventually buried in the sand, the pelagic, where plastic is floating neutrally buoyant in the water and the benthic, where plastic is sunken to the seafloor. Additionally, two different locations were investigated, where tests are technically and economically feasible and environmentally relevant. The field test systems were first developed in the Mediterranean Sea (at the islands of Elba and Pianosa, Italy) and further refined in Southeast (SE) Asia (Pulau Bangka, NE Sulawesi, Indonesia).

For biodegradable plastics, biodegradation is typically assessed with respirometric methods in closed lab test systems, where oxygen consumption or CO_2 evolution (and/or CH_4 under anoxic conditions) is measured over time (e.g. [48]). Disintegration occurs as a consequence of biodegradation, however fragmentation and disintegration of plastic, especially under field conditions, can also have purely physical (e.g. UV light, heat, abrasion, mechanical stress) e.g. [69] and chemical (hydrolysis, oxidation) causes.

In this study we used the degree of disintegration of the test material as a proxy for the biodegradation under the condition that (a) the material has been proven to biodegrade under laboratory conditions, hence is biodegradable and (b) under the assumption that our test systems are able to exclude physical forces efficiently enough that disintegration is primarily caused by the metabolic action of microorganisms.

Materials and methods

Test materials

To validate the newly developed test systems, the disintegration of a polyhydroxyalkanoate copolymer (PHA, MIREL® P5001, Metabolix, Cambridge, USA)—a bio-based, bacteria-derived, biodegradable material with a film thickness of 85 μm—was used as a positive control. A non-additivated low-density polyethylene (LDPE, LUPOLEN 2420K, LyondellBasell, USA) film with a thickness of 30 μm was used as a negative control. PE is the most common and most abundant material for light packaging and shopping bags and without prior physical (e.g. UV, heat) treatment is regarded as non-biodegradable [75, also e.g. 76].

Test systems and settings

HYDRA test frame. The materials were mounted in a holder termed the 'HYDRA® test frame' (Fig 1) to protect the samples during exposure against physical stress and to prevent loss of larger fragments after the onset of eventual disintegration. In the Mediterranean Sea tests, the film specimens were covered on both sides with a plastic grid of LDPE (POLY-NET, NSW-General Cable, Nordenham, Germany), with diamond-shaped meshes of 4 x 4 mm size. To be in accordance with standard methods for compost [4], after the successful experiments in the Mediterranean Sea a polyester mesh (PES, SEFAR, Heiden, Switzerland) of 2 x 2 mm mesh size was chosen for the next generation of HYDRA test frames and their subsequent application in another climate zone (tropical SE Asia). This also had the advantage of a better retention of smaller fragments. The exposed area of test material not covered by the filaments of the mesh remained almost the same (51% vs. 52%) and the mesh was not tightly adhering to the film to ensure the complete exposure to water. The specimens covered in mesh were fixed between two plastic frames (PE-HD 300, Technoplast, Lahnstein, Germany) with 3 mm thickness and of 260 x 200 mm external and 200 x 160 mm internal dimensions leaving a surface of 320 cm^2 of material directly exposed. The frames, the mesh and the test material were then assembled with plastic bolts and nuts (Nylon 6.6, www.kunststoffschraube.de, Singen, Germany) and each test frame was individually tagged with a code made from cable markers

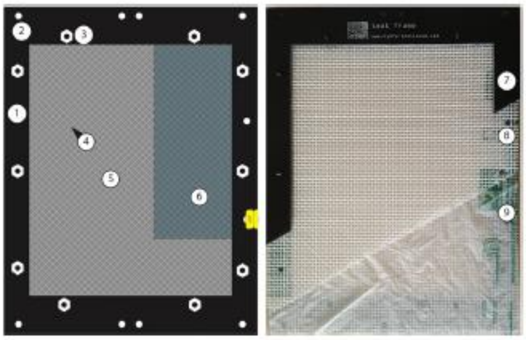

Fig 1. HYDRA test frame. Left panel: Scheme of test frame. (1) upper frame, (2) holes for fixing the frame to sample holders, (3) plastic nuts, (4) mesh covering the test material, (5) test material (film), (6) area for subsamples. Right panel: photo of HYDRA test frame, cut open to show different layers. (7) upper frame, (8) upper protective polyester mesh (modified to 2 x 2 mm), (9) test material (plastic bag), seen through film: lower mesh, lower frame.

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(HellermannTyton, Tornesch, Germany) fixed with a cable tie. The dimensions of the test items were chosen to provide enough material for subsampling (Fig 1, left) for further analyses.

Field tests. Three habitats (eulittoral, pelagic and benthic, Fig 2) were chosen to test the disintegration of biodegradable polymers in the sea, reflecting three common scenarios where (conventional) plastic litter is found in the ocean [74, 77].

For each habitat, a specific support structure for the test frames was developed (see below).

Field test locations

Matrices: Seawater and sediment as incubation media for the eulittoral (field and mesocosm) and benthic (mesocosm) tests. Natural Mediterranean seawater was taken at the boat slip at Seccheto, Isola d'Elba, Italy (42°44'06.5"N 010°10'33.5"E) and was used to wash the sediment and to fill the mesocosms. Natural marine sediment of siliclastic origin for the eulittoral (field and mesocosm) tests was retrieved at about 0.1 m water depth from the beach of Fetovaia, Isola d'Elba, Italy, (42°44'00.1"N 010°09'15.3"E) and is called "beach sediment". Carbonate sediment for the benthic mesocosm tests was collected from the seafloor at 40 m depth off Isola di Pianosa, National Park Tuscan Archipelago, Italy, (42°34'41.4"N 010°06'30.6"E) and is called "seafloor sediment". The sediment was wet sieved with seawater through a 10 mm mesh in order to eliminate coarse particles such as stones and shells and was resuspended several times to flush out very fine particles.

Study 1: Field experiments Mediterranean Sea. From April 2014 to October 2016 the eulittoral test system as described below was set up in a former saline basin on the Island of Elba, Terme di San Giovanni, Portoferraio (42°48'12.1"N 010°19'01.0"E). This location was chosen because of its unique structure: it is protected against waves and storms by a seawall while still interacting with the open sea by means of several inlets. There is a small irrigation trench that occasionally brings some freshwater runoff to the basin. The ecological character of the site is that of a typical Mediterranean coastal lagoon with weak estuarine influence. Beach sediment was prepared for the eulittoral tests as described above.

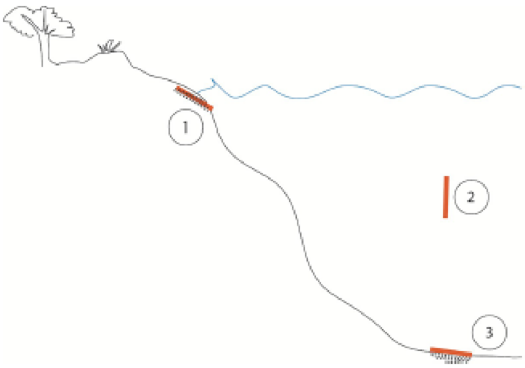

Fig 2. Schematic illustration of coastal habitats. (1) Eulittoral: intertidal beach scenario. Dots around samples symbolize sediment. (2) Pelagic: water column scenario. (3) Benthic: seafloor scenario. Dots below samples symbolize sediment.

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The pelagic and benthic tests were performed from June 2014 to October 2016 in the marine protected area of the National Park Tuscan Archipelago off the island of Pianosa (42° 34'41.4"N 010°06'30.6"E). The ecological character of this site is that of a typical Mediterranean coastal habitat with low anthropogenic impact and the risk of loss or disturbance by human activities was regarded as very low.

Eulittoral field test system

This test system mimicked an intertidal sandy beach in which plastic was buried and experienced changing conditions of being wetted and falling dry with the fluctuations of the sea level caused by tides and waves (Fig 3). A plastic (PP) bin of approx. 60 L volume was used to confine the sediment and the samples. The bottom of the bin was perforated with holes of 25 mm diameter to allow the ambient water to infiltrate. Two layers of plastic mesh (PVC-covered glass fiber 1 x 1 mm and polyester gauze 280 x 280 μm were placed above the holes to prevent the loss of sediment. A layer of 17 cm of beach sand was filled into the bin and a plastic pipe of 32 mm diameter, covered by fine mesh at the top opening, was installed as a short-cut for the rising and falling water to facilitate the drainage of the sediment. Three test frames were buried at a sediment depth of 10 cm with an inclination of about 11° from horizontal to allow the overlaying water to run off after each flood event. The filled bins were placed in groups of five on a wooden rack in order to position the test specimens in the mid-water line in a coastal lagoon. The rack structures and bins were covered by wire barbs to prevent disturbance from birds.

Pelagic field test system

This test system represented the habitat of the free water column where the plastic was neutrally buoyant and was in contact with only seawater as a matrix (Fig 4). The test frames were fixed with cable ties perpendicularly on top of each other to a plastic bar, four of which were mounted to a plastic cylinder (PE-HD 300, Technoplast, Lahnstein, Germany) with stainless steel bolts and nuts to form 4 radial wings. The cylinder was suspended upright at a water depth of about 20 m from a float with a lift of approximately 5 L and kept in place by a concrete anchor weight (50 kg) at the seafloor; this anchor was connected by a stainless steel cable with

Fig 3. Eulittoral test system. Top left: cross section through bin containing beach sand and samples. (1) wire barbs to deter birds, (2) 60-L plastic bin, (3) sand from a local beach, (4) test item frame, (5) fine mesh (280 μm), (6) coarse mesh (1000 μm), (7) perforations in bottom of the bin, (8) equilibration pipe, (9) fine mesh (280 μm) on the top of the pipe to allow for seawater outflow at high tide. Top center: 3 specimens in the test bin before covering with an additional layer of sand. Top right: test bin at high tide. Bottom left: wooden rack with 5 test bins at midwater. Bottom center: wooden rack with test bins at lower tide. Bottom right: schematic illustration of the eulittoral test system. (1) wooden posts, (2) wooden plank to support the bins, (3) metal chain to adjust the plank, (4) test bin, (5) high water level, (6) mid-water line, (7) low water level.

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Fig 4. Pelagic test system. Left: schematic illustration. (1) test materials in frames with mesh, (2) plastic pipe suspended from a float at 20 m water depth with specimens radially attached, (3) float, (4) steel cable to anchor stone. Upper left: detail of cylindrical rack with specimens attached radially, upper right and lower left: divers at pelagic test system at 20 m water depth. Lower right: detail of specimen in situ, note biofilm after 2 weeks of exposure (Mediterranean Sea).

https://doi.org/10.1371/journal.pone.0236579.g004

stainless steel bolts and nuts, or shackles. To prevent corrosion the steel cables were equipped with zinc anodes, fixed with stainless steel bolts and nuts.

Benthic field test system

This test system represented the habitat of the seafloor where the plastic was in contact with seawater and sediment as matrices (Fig 5). 3 x 5 test specimens were mounted on a rack of plastic bars and placed on the seafloor at approximately 40 m (Mediterranean Sea) or 32 m (SE Asia) water depth. Each rack was tied to the anchor block of the pelagic test system with a stainless steel cable and fixed to the sediment surface with U-shaped iron bars.

Study 2: Field experiments Indonesia. From March 2017 to October 2018 pelagic and benthic tests were performed in Sahaong Bay, Pulau Bangka, NE Sulawesi, Indonesia (01°

Fig 5. Benthic test system. Right: schematic illustration. (1) test materials in frames with mesh, (2) automated temperature logger attached to rack, (5) anchor stone, also for pelagic test system (see Fig 4), (6) plastic rack with specimens in test frames attached, (7) steel cable to anchor stone. Upper row: divers at benthic test system at 40 m water depth (Mediterranean Sea), note sediment and debris on specimens. Lower left: divers detach test frame, fixed with cable ties to the rack. Lower right: specimens are packed individually into PE plastic bags for further treatment in the laboratory.

https://doi.org/10.1371/journal.pone.0236579.g005

44'35.4"N 125°09'09.3"E). This location was chosen because it has been used for generations by local people to permanently anchor floating fishing huts (therefore a historical proof of good storm protection). The bay is very narrow and not suited for fishing methods that might have interfered with the test systems such as purse seining or trawling. The benthic system was deployed at a water depth of 32 m on sand to avoid the coral reef. The pelagic test was suspended in 20 m water depth. The ecological character of the site is that of a typical coastal area in the wet tropics, with high water temperature all year round and elevated nutrient content due to terrestrial run-off.

As a modification to the experiments in the Mediterranean Sea the mesh used for all test frames was 2 x 2 mm (Fig 1). There were no eulittoral tests done.

Study 3: Mesocosm experiments with Mediterranean Sea matrices. The mesocosm experiments simulated, in a multi-100-liter tank under controlled conditions beyond laboratory flask scale (usually a few 100 mL of volume), the degradation of the polymers PHA and LDPE in the marine environment in three coastal habitats: eulittoral, pelagic and benthic (Fig 6). These habitats were mimicked in a combined tank system as follows: PE-HD plastic tanks (Dolav GmbH, Bad Salzuflen) with inner dimensions 93 x 113 x 60 cm were set up in triplicates in a climate room at 21°C. Each set consisted of the eulittoral test tank placed on top of the tank with the benthic/pelagic test system, connected by a closed-system circuit of about 400 L seawater. Water was pumped into the upper tank in a way that simulated a semidiurnal tide, creating complete flooding every 12 h and a complete draining 6 h later. Tests were conducted twice for about 10 months each and termed year 1 (yr1) and year (yr2), with 4 sampling time intervals each. Before repeating the test, the matrices water and sediment were renewed.

Eulittoral mesocosm test system

The top tank (Fig 6) mimicked the eulittoral (intertidal) scenario and was filled with a layer of 15 cm of beach sediment. The incoming water was led by a hose to a perforated pipe (diam. 12 mm, L = 1 m) which was laid onto the sediment surface. The water inlet was connected to the

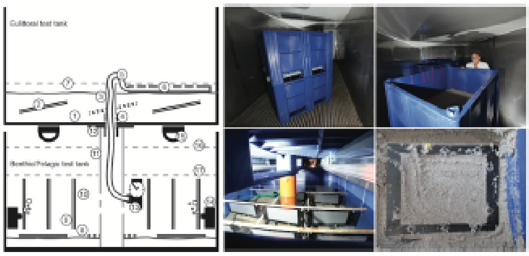

Fig 6. Mesocosm tank system. Left: schematic illustration. Upper left: upper tank, which mimicked the eulittoral (intertidal beach scenario) habitat. (1) beach sand, (2) test frames, (3) drainage pipe connected to lower tank, (4) perforation to drain sediment into (3), (5) hose connected to (13) delivering water to upper tank via (6) a perforated pipe, (7) high-water line in upper tank. Lower left: lower tank which mimicked the pelagic (water column scenario) and the benthic (sublittoral, seafloor scenario, sediment-water interface) habitat. (8) sediment surface, (9) pelagic test frames pending in the water, (10) water, (11) support pipe, connecting lower and upper tank, (12) flange as connector and seal between upper and lower tank, (13) pump with timer delivering water from lower to upper tank, (14) circulation pump for lower tank, (15) aquarium lamps 12h/12h, (16) high-water level, (17) low-water level. Upper center: overview of the mesocosm tank system. Upper right: view into the upper tank with eulittoral test. Lower center: view into the lower tank with pelagic and benthic tests. The pelagic samples were hanging in the water and the benthic samples were placed on the sediment on the tank floor. Lower right: view onto a sample, which was buried in the eulittoral sediment.

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benthic/pelagic test tank below by an EHEIM compact 600 pump (Deizisau, Germany) with an adjustable flow of 250–600 L/h. The upper tank had an outlet in the center of the bottom (diam. 50 mm) which was covered by gauze (polyester, 280 μm mesh, SEFAR, Heiden, Switzerland) to prevent sediment loss. The pumping rate was adjusted to balance the inflow with the outflow by passive drainage through the bottom outlet. Twice a day the water level was risen above sediment level by pumping up seawater from the benthic/pelagic test tank below. When the pump was stopped the water was allowed to passively drain through the bottom of the tank, with the consequence of sediment and samples slowly falling dry. Samples mounted in HYDRA test frames were buried in the sand at 5–10 cm depth with an inclination of 11° from horizontal to prevent water from being trapped on the film at falling water level during the simulated tidal cycles. At the end of a test interval samples were carefully dug out of the sediment and processed as described below.

Combined benthic and pelagic mesocosm test system

The benthic/pelagic test tank below the eulittoral test tank (Fig 6) was filled with a layer of 5 cm of seafloor sediment. Test frames were placed horizontally on the sediment surface and weighted down with small blocks of granite to prevent them from being moved by the water flow. The tank was filled with 400 L of natural seawater.

For the pelagic tests, samples mounted in HYDRA test frames were hung from a rack perpendicularly in the water column. The water was continuously moved by a water EHEIM compact 300 pump with a rate of about 300 L/h. The tank was illuminated from above in a 12/12 h light/dark rhythm by 2 BIOLUX L 36W/965 fluorescent lamps (OSRAM, Munich, Germany) with a nominal luminous flux of 2300 lm each. The water bulk was connected to the eulittoral test set on top and cycled by a pump as described above. At the end of each test interval polymer samples were retrieved from the tanks and processed as described below.

Environmental conditions in the different test settings

In order to characterize the natural and the mesocosm habitats the environmental parameters such as temperature, light, salinity, pH, oxygenation were monitored. Additionally, samples of the matrices water, sediment and porewater were taken and analyzed for physical, chemical and biogeochemical properties with standard methods (e.g. [78]). Selected data are given where the environmental conditions are relevant to better understand the methods and their evaluation. The full characterization of the experimental sites will be published elsewhere.

A selection of nutrient-related parameters (C, N, P, Si compounds), photopigments and metals as well as potentially toxic substances such as arsenic and heavy metals (cadmium, chromium, copper, lead, mercury, nickel, zinc), and a catalogue of anthropogenic persistent organic pollutants (POPs) were analyzed in water and sediment from the tanks and from the field sites by external accredited analytical services (Institute Dr. Nowak GmbH & Co. KG, Ottersberg, Germany and SGS-WLN Analytical Services, Manado, Indonesia) according to standard methods.

The chemical analysis was mainly conducted to exclude extreme conditions such as very high nutrients or toxins like heavy metals or POPs in high concentrations that potentially could have inhibited biodegradation. None of the parameters measured was found in high values or unusual of the surrounding biogeochemical context. The detailed list of parameters, methods and detection limits as well as the detailed results will be published elsewhere.

Water temperature

Water temperature was automatically recorded with HOBO UA-002-64 Pendant temperature/light loggers (Onset Computer Corporation, Bourne, MA, USA) or TinyTag Aquatic 2 –TG-

4100 data loggers (Gemini Data Loggers Ltd, Chichester, West Sussex, UK), attached directly to the test devices.

Light

The light regime at the pelagic/benthic field test systems was assessed exemplarily by measuring a depth profile of the photosynthetically available radiation (PAR) within the sensor range of 400–700 nm; this was done by a diver from the water surface to the benthic test systems at the seafloor with a LiCor PAR Sensor LI-192 (LICOR Inc., USA) in an underwater housing on sunny days at midday (Mediterranean Sea) or with a HOBO Pendant temperature/light logger in SE Asia. In the Mediterranean Sea the light intensity at the pelagic test system (20 m depth) was 13% and at the benthic test system (40 m depth) 3% of the surface intensity. In SE Asia the light intensity at the pelagic test system (20 m depth) was varying between 1.2 and 2% and at the benthic test system (32 m depth) it was 0.5% of the surface intensity. UV light which is important as a physical agent for polymer degradation in above water environments is rapidly attenuated with depth under water [e.g. 79, 80] and negligible at the depths of our experiments (pelagic: 20 m; benthic: 32 m (SE Asia)/40 m (Mediterranean Sea)). Thus, it was not measured here.

Salinity, pH and oxygen

Salinity, pH and O_2 concentrations were measured in samples from each of the three field sites: from the free water around the benthic and pelagic test systems, from the sediment porewater retrieved from the bins of the eulittoral test system at the level of the test material, and from the mesocosm tanks. Measurements were taken using a TetraCon® 925 conductivity sensor, a SenTix® 940 pH sensor SenTix® 940, and a FDO® 925 oxygen sensor attached to a Multi 3420 (WTW, Weilheim).

Mesocosm tests

The measured water temperature was 20.5±1˚C (mean±standard deviation) (set: 21˚C) and mean light intensity on the sediment surface of the benthic tests was 11.56 μmol photons·m^{-2}·s^{-1}. Salinity was about 39 with a variation of ±1 for both years (set: 38.5). The pH was stable at 8.1±0.1 and the oxygen concentration was close to air saturation (98±2%). Water chemistry: Throughout the experiments, water in all tanks and porewater from the eulittoral sand contained low to moderate levels of nutrient-related parameters (TN, NO_2, NO_3, NH_4, TP, TOC, DOC, Chl *a*, Phaeophytin, etc.). Compared to the field data nutrient concentrations were similar or only slightly elevated. Dissolved aluminium was detected at low concentration. None of the toxic substances as heavy metals, organotin compounds and POPs were detected. Sedimentology and sediment chemistry: The beach sand of the eulittoral tests was mainly of siliclastic origin and for its grain size was classified as medium sand [81].

The sediment used for the benthic experiments was composed mainly of carbonate minerals and characterized as fine sand in both years. Accordingly, porosity and permeability were slightly lower for both sands in the second year (Table 1) whereas nutrient contents were similar and low. Metal concentrations were low or below detection limit. None of the known anthropogenic toxins analyzed in the sediments used for the experiments were detected.

Mediterranean Sea field test–eulittoral

The temperatures in the eulittoral test bins roughly followed the temperature of the ambient water with the daily and the tidal cycles. Daily mean temperatures of about 25˚C (yr1) and

Table 1. Physical properties of the sediments from the field and mesocosm experiments.

	Mediterranean field			Mediterranean mesocosm				Southeast Asia field
	benthic	eulittoral		benthic		eulittoral		benthic
		year 1	year 2	year 1	year 2	year 1	year 2	
Grain size mean ± SD (μm)	*213 ± 26*	*214 ± 5*	*278 ± 5*	*181 ± 23*	*146 ± 47*	*278 ± 14*	*206 ± 9*	*197 ± 47*
Permeability mean ± SD (10^{-11} m^{-2})	*1.12 ± 0.9*	*7.46 ± 1.5*	*20.06 ± 2.0*	*2.60 ± 0.6*	*2.40 ± 1.2*	*17.9 ± 0.6*	*9.54 ± 2.2*	*2.26 ± 0.8*
Porosity mean ± SD	*0.67 ± 0.6*	*0.41 ± 0.2*	*0.43 ± 0.5*	*0.62 ± 0.4*	*0.51 ± 0.6*	*0.45 ± 0.2*	*0.42 ± 0.8*	*0.54 ± 0.1*

*SD = standard deviation

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26°C (yr2) were highest between June and September and lowest mid-October and March with around 12°C (yr1 and 2). The lowest daily minimum was -1.0°C in January 2016. Fluctuations were pronounced, and the night temperatures were usually lower (by up to 5°C) than in the surrounding water. Salinity of seawater in the test bins was most of the time in the range of 36–42; lowest values were almost 0, highest values reached 70. The pH was around 7.6–8.2; lowest values were below 6.8, highest values reached 9. The oxygen concentration in the test bins was mostly between 20 and 80%, and rarely reached 100% air saturation (see also Table 2).

Water chemistry: The porewater in the bins throughout the experiments had low to moderate levels of nutrient-related parameters, however compared to the benthic and pelagic test sites they were slightly elevated. Dissolved Fe, Mn and Al were detected at low concentrations. None of the POPs tested were detected. Sedimentology and sediment chemistry: The beach sand used in the test bins was fine (mean 214±5 μm yr1) and medium (mean 278±5 μm yr2) sand. The porosity and permeability were therefore higher in the second year (Table 1). Nutrient concentrations were low or b.d.l. and of the metals analyzed only Zn, Ni and Cr were detected in low concentrations. Organotin compounds, pesticides and their metabolites could not be detected in the sediment.

Table 2. Water temperature, salinity, pH and oxygen concentrations of the field and mesocosm experiments.

	Mediterranean field				Southeast Asia field		Mediterranean mesocosm
	eulittoral		pelagic	benthic	pela**gic	benthic	all habitats
	year 1	year 2					
Highest daily max. temp. (°C)	*34.5*	*38.4*	*25*	*20*	*28.6±0.4***	*28.6±0.5***	*20.5±1.0***
Highest daily mean temp. (°C)	*25*	*30*					
Lowest daily mean temp. (°C)	*12*	*11*	*14*				
Lowest daily min. temp. (°C)	*-0.8*	*-1.0*					
Salinity range	*36–42**		*38*		*34.0±0.4***	*33.9±0.2***	*39.0±1.0***
Minimum salinity	*~0**						
Maximum salinity	*70**						
Mean pH	*7.6–8.2**		*8.2*		*8.1±0.1***		*8.1±0.1***
Minimum pH	*6.8**						
Maximum pH	*9.0**						
Oxygen (% air saturation)	*20–80* rarely ~100**		*~100*		*100.8±4.6***	*101.3±6.8***	*98.0±2.0***

*The data for Mediterranean field eulittoral were analyzed from sediment porewater.

**mean ± standard deviation.

https://doi.org/10.1371/journal.pone.0236579.t002

Mediterranean Sea field tests–pelagic and benthic

The temperature at the two stations diverged over the course of a year due to stratification of the water column from spring to late autumn, when the temperatures in the different depths merged again. Highest daily mean temperatures were about 25°C at the pelagic test site and 20°C at the benthic test site. Lowest temperatures were recorded early February until mid-May with around 14°C at both sites. Fluctuations between daily minimum and maximum temperatures sometimes ranged 4–8°C (pelagic) and 4–5°C (benthic). At the pelagic tests at 20 m depth temperature fluctuations were more pronounced during spring and summer, reflecting an irregular mixing with the surface waters and a gradual downward migration of the thermocline through the water column. At the benthic test, autumn fluctuations were more pronounced due to occasional storms that led to a mixing of the water column. At the depth of the pelagic test system (20 m) solar irradiation was about 13% and at the benthic test system (40 m) about 3% of the surface level. Salinity was at 38, pH was 8.2 and oxygen content was around 100% air saturation at both sites.

Pelagic and benthic water chemistry: The water at both test sites, as well as the porewater at the benthic test site, had low levels of nutrient-related parameters throughout the experiments. Dissolved Al could be repeatedly detected at low concentrations, as well as iron and manganese in the second year. Other metals were b.d.l.. No toxins or POPs were detected. Benthic sedimentology and sediment chemistry: The benthic sand was fine sand (mean 213±26 μm) with low concentrations of nutrients and some metals (Fe, Mn, Pb, Cr). Organotin compounds and pesticides and their metabolites could not be detected. No toxins or POPs were detected in the sediment.

SE Asia field tests–pelagic and benthic

The temperature at the two stations was the same throughout the year (pelagic test: 28.6 ±0.4°C, benthic test: 28.6±0.5°C). At the depth of the pelagic test system (20 m) solar irradiation was about 1.5% and at the benthic test system (31 m) about 0.5% of the surface level. The salinity at the two stations was similar throughout the year. The mean salinity was 34.0±0.4 at the pelagic test, and 33.9±0.2 at the benthic test. A pH of 8.1±0.1 was the same at both test sites, and oxygen concentrations were 100.8±4.6% air saturation at the pelagic test site and 101.3±6.8% at the benthic test site.

Pelagic and benthic water chemistry: The water at both test sites as well as the porewater at the benthic test site had low levels of most nutrient-related parameters throughout the experiments. The silica, chlorophyll *a* and phaeophytin concentrations however were higher than at the test sites in the Mediterranean Sea. Metal concentrations were all b.d.l., only Cd was detected once in very low concentrations. No toxic substances or POPs were detected. Benthic sedimentology and sediment chemistry: The benthic sand was fine sand (mean 197±47 μm) with low nutrients and low concentrations of some metals (Fe, Mn, Pb, Cr). No toxins or POPs were detected in the sediment.

Plastic sampling and disintegration analysis

After a given time interval the samples were detached from their racks (pelagic, benthic) or dug out of the sediment (eulittoral), gently rinsed in ambient water, packed individually in PE plastic bags and kept wet until further treatment the same day. In the laboratory, the frame was opened, the material was carefully detached from the upper frame and mesh and photographed immersed in seawater in a tray with a digital camera (Canon EOS 5DMkII, or a SONY A7 III, with a 100 mm or 50 mm macro lens). Subsamples were taken for later optional microscopic and molecular analyses, which are not subject of this publication. The remaining sample was rinsed in deionized water, air-dried and archived.

The disintegration of each specimen was determined photogrammetrically [40]. Dried samples from the Mediterranean Sea experiments were scanned on a flatbed scanner (LIDE 210, Canon Inc.). The samples from the SE Asia experiments were photographed immediately after retrieval. The images thus obtained were analyzed for area loss using ImageJ software (https://imagej.nih.gov/ij/) or GIMP (http://www.gimp.org/) by outlining the boundaries of the remaining test material that had been exposed and not covered by the frame. Subsequently, the ratio of total area vs. lost area was calculated as % area loss.

Ethical statement

Sampling of water and sediment in the protected area of the Island of Pianosa was performed with the research permit n.3063/19.05.2014 from the National Park Tuscan Archipelago, Portoferraio. Research in Indonesia was conducted under the research permits no. 71 and 72/SIP/FRP/E5/Dit.KI/III/2017 and extensions granted by the Indonesian Government Ministry of Research, Technology and Higher Education, RISTEK-DIKTI. With regard to the photographs shown for illustration the individuals (all coauthors) in this manuscript have given written informed consent (as outlined in PLOS consent form) to publish these case details.

Results

Study 1: Field Mediterranean sea

All samples were retrieved after the planned exposure time, no sample was damaged nor lost.

Visual appearance of the samples

For LDPE, after testing the only visible material alterations were superficial discolorations, presumably from mineral precipitations, biofilm and colored organisms, e.g. sponges. Exemplary images are shown in Fig 7. In the PHA specimens, the first visible signs of disintegration were translucent areas due to progressive thinning of the polymer films, followed by the appearance of cracks, holes and finally fragmentation in all tests. Most samples showed a change in color during the time of the experiment, attributed to the formation of biofilm and mineral precipitates, rendering image analysis difficult in some cases.

Polymer disintegration

For LDPE, disintegration was not detected in any of the tests, and will not be described further in the results section. PHA disintegration was observed in all tests.

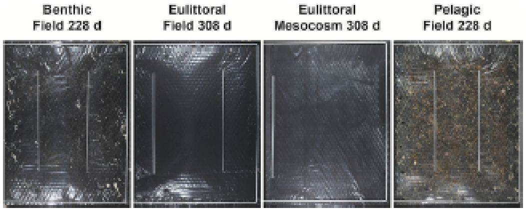

Fig 7. Exemplary photos of LDPE samples from disintegration tests. Freshly retrieved samples from field and mesocosm experiments under Mediterranean Sea conditions. Note: the metal bars in the images were put onto the film to keep the sample under water for photography.

https://doi.org/10.1371/journal.pone.0236579.g007

Eulittoral test (intertidal beach scenario)

PHA disintegrated in both years, reaching more than 50% after 5 months in yr1 in most replicates. Some replicates however showed only minimal disintegration of between 5 and 20% after 5 to 10 months. After 22 months all five replicates were disintegrated to over 65%. In the yr2 experiment PHA disintegration was slower and reached just over 30% after 10 months for one replicate. All replicates were disintegrated to more than 10% after 5 months. Generally, the disintegration of all replicates of all sampling intervals was heterogeneous.

Benthic test (sublittoral seafloor scenario)

PHA showed disintegration, which differed however by year. One sample showed disintegration of 31% after 5 months and two samples 60–75% after 22 months. The disintegration of all other samples in both years was below 5%. In the yr2 experiment, PHA disintegration was slower and only one sample reached more than 6%. Generally, the disintegration of all replicates was heterogeneous.

Pelagic test (water column scenario)

At sampling, all specimens were still intact after the exposure time of max. 22 months. In some specimens, a thinning of the material was observed, visible by more translucent areas. Small holes were detected in only a few samples, but accounted for less than 1% area loss.

Study 2: Field tests SE Asia

Benthic test (sublittoral seafloor scenario). In the benthic test of the SE Asia study, PHA showed rapid disintegration, with material loss already well visible after 19 days of exposure (Fig 8). After 90 d most of the test material was gone in all 3 replicates (exemplarily: Fig 8). A conspicuous longitudinal crack was observed in all specimens after exposure, in the cases where there was still material left (Fig 8). This is assumed to have been the consequence of a systematic material irregularity caused during the film processing on a small laboratory-scale extruder rather than on an industrial machine. The crack was not taken into account as loss by

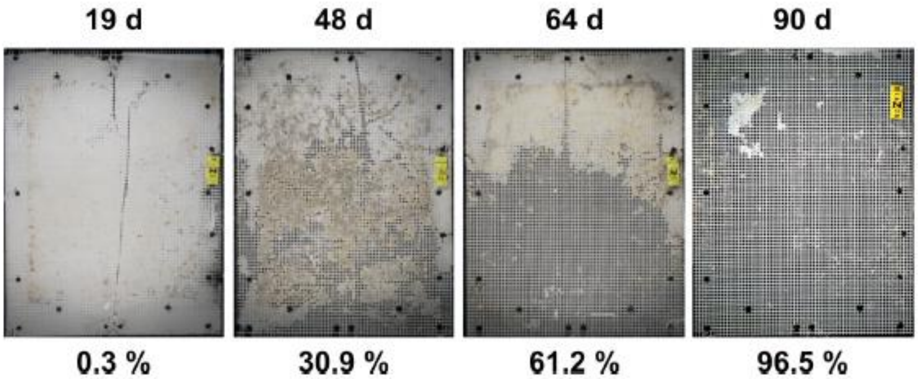

Fig 8. Exemplary photos of PHA samples from benthic field disintegration tests in SE Asia. Photos of 1 replicate from 4 exposure intervals each, with disintegration per sample in % area loss below each image. Note: the values are calculated only from the exposed area not covered by the frame.

https://doi.org/10.1371/journal.pone.0236579.g008

disintegration but ignored for the area measurement. The inhomogeneous disintegration of the samples, i.e. higher material loss at the bottom edge might be due to the slight inclination of the seafloor leading to the accumulation of a layer of fine sediment within the test frame building up from the lower part.

Pelagic test (water column scenario). Disintegration was observed in all PHA samples, however, the accurate measurement of the lost area was not possible due to heavy fouling of the support structure and the polymer itself (Fig 9). Also, the layer of the fouling organisms (mainly encrusting red algae, sponges, hydrozoans and bryozoans) often was bonding the mesh and the polymer together. Splitting open the test frame during post-sampling in the lab

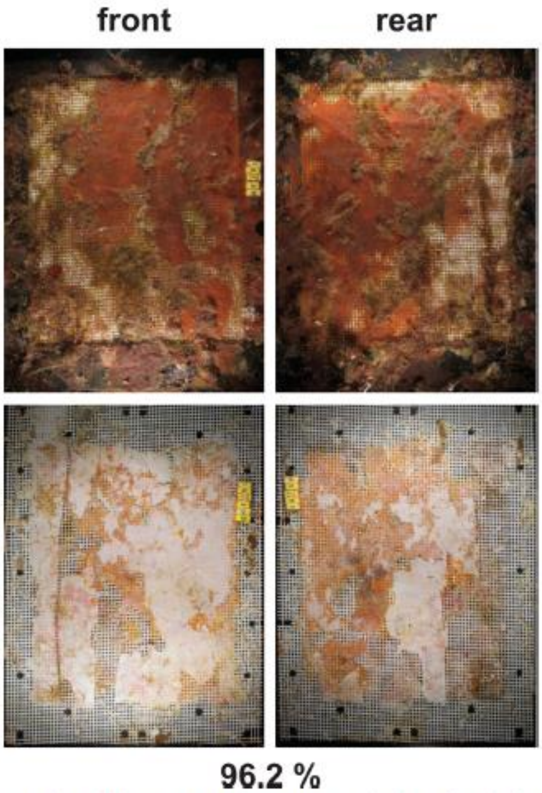

Fig 9. Pelagic field test SE Asia: PHA disintegration. Exemplary photos of a sample after 210 d of exposure. Top: specimens retrieved from the field, note the dense fouling. Images left and right show front and rear of the same sample. B: specimen unpacked, note the almost complete disintegration under the frame, and no fouling there. The light surface is mostly the crust of coralline algae remaining after the disintegration of the test material. The test material is largely disintegrated, as expressed by the percentage of area loss. Note the value given is rather an overestimation due to the likely mechanical influence of macro-organisms (see main text).

https://doi.org/10.1371/journal.pone.0236579.g009

caused further fragmentation and thus a mechanical destruction of the materials as an artefact. In these cases, both halves of the test frame with the adhering sample were photographed and subjected to analysis (Fig 9). Another factor of sample deterioration in the pelagic tests was linked to animals found in between the meshes. Presumably, crabs and clams had settled as larvae on the test material and after having grown above mesh size they had been trapped between the two layers of protecting mesh. Traces of their movements point to these animals having mechanically destroyed the polymer. Because the degree of error could not be assessed a numerical quantification of the disintegration in the pelagic test in SE Asia is to be treated with caution, and rather seen as an overestimation. It is notable that outside the area of interest, i.e. under the supporting frame where only microbes could biodegrade the samples, almost all material was disintegrated (Fig 9, bottom).

Study 3: Mesocosm tests with Mediterranean seawater and sediment as matrices

Polymer disintegration. PHA samples showed disintegration in all three tested habitats eulittoral, benthic and pelagic. The disintegration gradually progressed with time, with most samples disintegrating less than 50% after 9–10 months of exposure. The rate of disintegration differed between habitats and was heterogeneous between replicate samples of one sampling interval, with values ranging e.g. from 7.4 to 46.7% after 152 d for the benthic test (exemplarily: Fig 10).

Additional observations

Macro-organism interaction with the test materials. Several measures were taken to prevent a negative impact by animals on the test system. However, some disturbances resulted from the interaction of (macro-) organisms with the exposed materials in the field, and to a lower extent also in the mesocosms.

Eulittoral field tests: The picking of birds in the eulittoral test bins was successfully prevented by wire barbs on top of the test system. Infauna like worms or clams were not observed

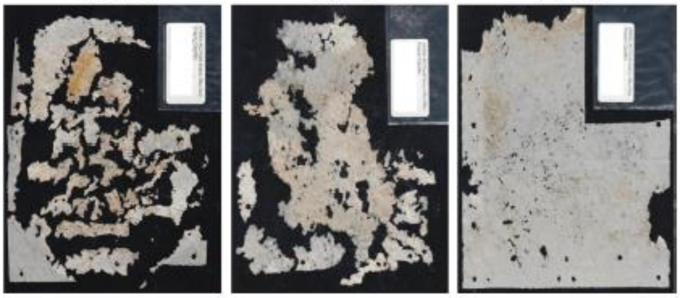

Fig 10. Photos of PHA samples from mesocosm benthic disintegration tests to illustrate the heterogeneity between replicates. Scan images of all 3 replicates from the mesocosm benthic test (sublittoral, seafloor scenario) after 152 d of exposure. Disintegration in % area loss below each image. Note the heterogeneous disintegration between the three replicates.

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Fig 11. Wooden post from eulittoral test rack. Post from untreated larch wood after 26 months of exposure at the Mediterranean test site. The wood is perforated by wood-boring bivalves (white tubes) and broken. Scale: white tube lower right is about 5 mm diameter.

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in the eulittoral test bins. A structural problem for the racks made from untreated larch wood resulted from the activity of wood-boring bivalves ("shipworms") that had destroyed the posts after two years to the brink of collapse (Fig 11).

Pelagic field tests: Fouling, i.e. the colonization of the structures by a community of larger sessile organisms (e.g. macroalgae, sponges, hydrozoa, bryozoan, ascidians, bivalves, tube-worms) was a major issue for the maintenance of the whole structure—from the steel cable to the floats, the plastic support cylinder and the test frames (Fig 9, top and Fig 12). Regular cleaning of the support structures (not the samples themselves) by divers was necessary to prevent the test systems from becoming too heavy. At the samples themselves the fouling amalgamated with the test materials, growing through the mesh. For heavily fouled samples it was often impossible to remove the overgrowth after sampling from the remaining polymer without creating further damage and influencing the result. Steel cables were chosen over plastic rope because turtles and some fish are known to snatch ropes while feeding on sponges and other encrusting organisms. However, on several occasions bite marks on the frames and mesh were observed, but a sample was never found bitten all the way to the specimen. On two

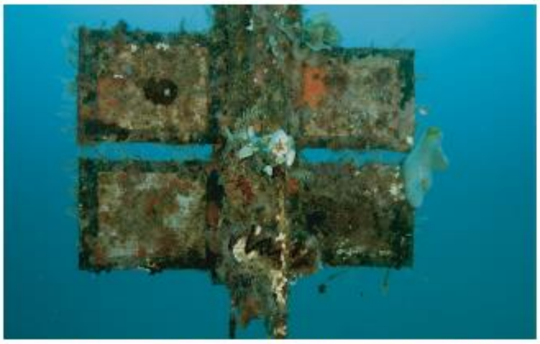

Fig 12. Fouling at pelagic test system SE Asia at -20 m. Sample frames and support structure were covered almost completely by sessile animals and algae. Note the fist-size oyster in lower center (zig-zag line). Exposure time 20 months.

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occasions cable ties that served to fix the codes to the samples were found cut open, and once a large puffer fish was observed grazing on the pelagic test system, having just bitten off a code tag.

Benthic field tests: The test frames were laid onto the sand bottom and fixed with steel bars. The flat rigid structures were readily populated by benthic fish such as gobies which dug out dens in the underlying sediment. Octopus were observed using the benthic samples as shelter and also sea cucumbers were found digging under the panels. Bioturbation presumably by sand-dwelling worms, bivalves and shrimp under and around the specimens was also observed having changed the sediment topography at the test sites at each sampling event. On some occasions, sediment and/or seagrass leaf debris was found to have accumulated on the benthic samples, but was absent at the next maintenance dive, indicating some water dynamics at the water-sediment interface.

Discussion

Field test systems allow for long-term observation under natural conditions

Three scenarios were chosen to mimic conditions at locations where dispersed plastic debris is commonly found in coastal marine areas: the beach scenario (eulittoral), the water column scenario (pelagic) and the seafloor scenario (benthic). The field test systems have repeatably proven their stability under natural coastal marine conditions in two climate zones over many months to years of exposure. However, the 22 months of exposure time in the Mediterranean pelagic tests (Isola di Pianosa, Tyrrhenian Sea) turned out to be too short to observe strong disintegration of the exposed materials. In experiments with the same polymer types where samples were suspended from fish farm cages, [29] found much faster disintegration, presumably due to faster microbial growth at a higher nutrient content of the surrounding water.

Samples were proven well protected against physical impact

The HYDRA test frames successfully provided protection from mechanical forces in all tests and not one sample was lost from the tests. The retrieval of almost intact sheets of the positive control material PHA after being exposed to currents and waves in the open water column for almost 2 years in the Mediterranean pelagic on the one hand, and the retrieval of heavily disintegrated, brittle samples from the SE Asia benthic impressively showed the efficiency. Previous studies used open frames without protective mesh or no frame at all to expose plastic film samples and reported complete loss of some samples during the exposure time [e.g. 19, 37]. The *gradual* material loss measured here as disintegration over time demonstrates the method chosen as suitable for long-term exposure experiments of biodegradable plastic films in the open aquatic environment.

This was also confirmed by the similar status of the test materials exposed in the mesocosm test. However, in all samples, there was a slight effect of the mesh visible at the test material surface with a differentiated thinning below the filaments and in the voids. Although the mesh was not adhering tightly there might have been some differentiations with regard to water and gas exchange, and biofilm formation. Different micro-habitat conditions could have led to the observed disintegration pattern reflecting the geometry of the mesh. However, these minor effects are seen as an acceptable trade-off for stability and operational safety of the experiments, i.e. the retrievability of the test materials after prolonged exposure time.

Mesocosm tests can fill the methodological gap between lab and field tests

The mesocosm tests also were proven practical and generally suited to run for a longer time period in a closed circuit. The salinity could be easily adjusted, and the pH was stable over the course of the experiment. In the pelagic and benthic tests however, photosynthetic biofilms may complicate the experiments by causing a patchy overgrowth on the samples. Being of a limited amount of water and sediment, the biotic community originating from an inoculum of random diversity can lead to the dominance of few organisms (cyanobacteria and/or algae) covering large areas in each of the mesocosm tanks. In order to avoid these differences, also between tanks, we recommend conducting the experiments in the dark. Also, higher but still physiologically relevant temperatures for the respective climate zone (e.g. 25°C in the Mediterranean tests) could be used to accelerate the processes and render the tests more efficient. The heterogeneity of the disintegration between replicate samples is not to be seen as an artefact of the mesocosm tank tests but was also observed between samples in the field tests. This is interpreted as a reflection of the patchiness of the microbial community according to small-scale changes of environmental conditions, as similarly observed also for example, in marine coastal sands (e.g. [82]). This could also explain the different disintegration rates between the field experiments and mesocosm experiments with sediments from the field sites.

Using disintegration as a proxy for biodegradation

In an open-system biodegradation test, where CO_2 or O_2 cannot be tracked directly with commonly available (i.e. not labelled) plastic materials, degree of disintegration is a feasible parameter to be measured in a simple and cost-efficient manner. The disintegration can however only be considered a valid proxy under the assumption that: 1) the physical forces are minimized or excluded in the open system tests and, more importantly, that the test material has shown to be biodegradable in a (standard) respirometric lab test (water: [48, 53, 54]; sediment-water interface: [49, 50]; beach sand: [51, 52, 83]). This is the case for the positive control/test material PHA Mirel P5001 that was also used in lab tests during the Open-Bio project. PHAs were also proven by others to fully biodegrade (PHB by [29] in seawater according to [48]; PHA Mirel P5001 by [84] in seawater according [48]; PHBV by [19] in seawater with biofilm from fish tank as inoculum).

As we were testing thin polymer film, we chose to measure area loss by photogrammetry instead of weight attrition [73] to assess the disintegration of the test material over time. Weight attrition might be suitable for water tests but can be easily biased by a variety of factors such as fouling organisms and adhering particles—if tests are done in contact with sediment—or by additional material loss during cleaning attempts.

By the assessment of lost area via image analysis we gained a hole/no-hole ratio after a certain exposure time. The method however intentionally ignored the third dimension of the material with the disadvantage of a technical lag phase until first holes were visible. The sometimes well discernible thinning of material was not taken into account and led to an underestimation of the disintegration at the beginning, extending the biogeochemical lag phase with a methodological lag of detectability. As soon as the material is heavily fragmented small particles might escape through the mesh leading to an overestimation of the disintegration at the very end of the experiment. Both effects will be more pronounced in the case of thicker materials. For accurate photogrammetry, standardized photos of fresh samples instead of scans of dried samples are better suited and it is recommended to put some effort into obtaining good image quality.

Environmental relevance and the importance of a positive control: Disintegration rate depends on the environmental setting

The disintegration rate of the same test material differed strongly between habitats and climate zones. A striking example is given by the comparison of the performance of the PHA samples:

in the Mediterranean pelagic tests (Isola di Pianosa) there was only little material degradation after 22 months, whereas in the benthic of SE Asia (Pulau Bangka, Sulawesi) all three replicates of the same material were almost completely disintegrated after 3 months. This emphasizes the necessity of including positive controls in all tests. These data also are a valuable indication that the test results from one specific environmental setting have to be put into an ecological context and do not represent the performance of a given material in the whole marine realm. Metadata relevant for physiological activity of microbes such as temperature, oxygen, pH, light intensity, salinity, nutrients, metals, as well as granulometry, porosity and permeability of the sediments are also necessary to be able to interpret and compare disintegration data. These parameters should be measured on site and, ideally, throughout the experiment.

Degradation under the frame differs from exposed area of interest

Due to the design of the HYDRA test frames, parts of the test material which were not intended as area of interest were covered. Only the material exposed to the matrices was analyzed as described. However, the shielding of some of the material by the frames brought along an unintentional co-testing of the material. In these conditions it can be assumed that disintegration derives solely from the action of microorganisms and that presumably only a very limited amount of oxygen is available. This gave hints for the anaerobic degradation of biodegradable plastic. Since some plastics may degrade faster under anoxic conditions, this observation should be addressed by a specific study.

Fouling may jeopardize measurements of pelagic field tests

The specimens exposed in the pelagic test system in SE Asia were quickly covered through heavy fouling. All the materials such as frames, mesh and support structures were already overgrown after a few months by e.g. coralline algae and sponges which could not be removed without strong physical impact on the test material—a factor that had been a priority to avoid in the experimental design. Due to rather large sampling intervals, the rapid succession of the organism community and the general impact of fouling could not be studied. A small-scale observation with regular samplings every few days to weeks would be required for a good temporal resolution to understand whether fouling would hinder or accelerate polymer degradation. A previous study in the Mediterranean Sea indicated a decreased rate of disintegration by fouling [29].

The pelagic test system is the least environmentally relevant but can deliver important insights

The habitats and locations reported in this work were chosen since they represent well the areas in which most plastic debris is found. The eulittoral test system is ideal to investigate materials with a specific density below that of seawater that initially float at the surface and can be washed ashore. This is the case for the most commonly used conventional polymers polyethylene and polypropylene, and also all items with a positive bulk buoyancy (e.g. capped bottles, foam), regardless of the material. The benthic tests represent well the seafloor scenario, the sink for most plastic materials [74, 77] due to biofilm formation. For this reason, the pelagic tests in which the materials are artificially kept from further sinking despite biofilm formation could be considered the least environmentally relevant for the study of plastic debris. However, these tests provide important information about the time during which the materials float in the water column. The pelagic test remains highly relevant to assess materials that are considered to be used directly in an aquatic environment, for example in aquaculture systems. In this case materials should be tested where they will be applied in the field.

Conclusions

Reliable systematic tests to investigate the biodegradability of plastics in nature are urgently needed to complete the environmental risk assessment of these materials entering the marine environment. The tests presented here are an efficient toolset allowing quantitative measurements under natural aquatic conditions.

Technically, all test systems were proven to be stable and are suited for use over several years to expose and test plastic films in coastal habitats. Some maintenance to the systems such as regular cleaning is required, especially in areas of high fouling. These test systems could also easily be transferred to other aquatic habitats and test sites and be adapted to test objects instead of films. The test frames sufficiently protected the samples and no mechanical damage of the specimens was detected and we are convinced that under such test conditions the observed disintegration was caused predominantly by biodegradation. Mesocosms are well suited for manipulative experiments above lab flask scale. However, results might deviate from field experiments. Controlled parameters such as temperature and also nutrient content could be set to optimum conditions within the physiological limit of the locations the matrices are collected from. More replicates with a smaller size and the exclusion of light could lead to a more consistent data set which is less affected by heterogeneity.

Eulittoral and benthic tests are considered the most realistic scenarios for biodegradable plastics most of which have a specific density >1, and from environmental observation of the fate of conventional plastic accumulating on beaches and the seafloor. Pelagic tests are mandatory for materials which are to be used in this habitat. Testing under anoxic conditions could give a deeper insight into the performance of biodegradable polymers in aquatic environments, as most sediments are reduced in or free of oxygen.

The disintegration rate of the same test material differs between habitats and climate zones. This should be accounted for by testing in different habitats and conditions and generating a set of metadata on the ecological context of the testing site.

The outcome of this work has supported the development of a new ISO standard: "ISO 22766 (en) Plastics—Determination of the degree of disintegration of plastic materials in marine habitats under real field conditions" [46].

The assessment of marine biodegradation of plastic materials with these test systems should serve to create basic knowledge, not as an advocacy for or against a technology.

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From Coral Triangle to Trash Triangle—How the Hot spot of Global Marine Biodiversity Is Threatened by Plastic Waste

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1 Introduction

Southeast Asia harbours the highest marine diversity of our planet. At the same time, the countries in the so-called Coral Triangle (CT; Fig. 1) have the highest potential/risk of plastic pollution to the marine environment. Biodiversity research is still struggling with the sheer inventory of biota, as many marine organisms already are under risk of becoming extinct by human influence. Many authors have reported about the occurrence of this type of pollution, including other marine debris in general, in this region, for instances in Bootless Bay, Motupore Island, Papua New Guinea [1], in Indonesia; Kupang [2], Bali [3], Manado [4], Ternate [5]. Most of them described the environmental condition of the areas as being full of waste, especially plastic debris, except Luwuk Peninsula, Indonesia, which Scaps and Runtukahu [6], about ten years ago, described in good condition with no debris.

Indonesia plays an important role in the CT region: it hosts marine mega-biodiversity, called "Amazon of the Ocean" with various resources of coral reefs, mangrove and seagrass ecosystems [8]. At the same time, the country is the second biggest polluter in the world, with an estimated production of about 3.22 million tons of plastic waste in 2010 [9]. This is triggered by the geography with its small-scale areas of regencies, cities and islands, and also, for instance, a medium-sized city like Manado (North Sulawesi, Indonesia) as a case study in the

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Fig. 1 Coral Triangle (CT) area [7]

CT area. In this city, waste management strategies are rudimentary, baseline data on sources, quantity and quality of plastic waste are lacking, and micro-plastic in special is hardly addressed, thus urgently needed risk assessment and mitigation concepts lack fundamental knowledge.

We provide observational data as beach clean-up reports, remotely operated vehicle (ROV) seafloor surveys and gut content analyses of fish, as the first collection of available information for this region. As a conclusion, we formulate further actions needed for Indonesia and globally to address the problem.

2 Waste Management in the City of Manado

2.1 Waste Discharges

Manado City (MC), the capital city of North Sulawesi Province, is located at the western part of Minahasa Peninsula in the NE of Sulawesi Island, a K-shaped island, in the middle of the Indonesian archipelago (Fig. 2). It is a medium-sized city, 15,726 ha [10], with a dense population of about half a million people. Right next to the city is Manado Bay and Bunaken Island, one of the iconic world-class destinations of diving tourism, and the Bunaken National Park (BNP). Manado is origin of a stream of mismanaged waste entering the ocean everyday, with different estimations, the highest being an assumed volume of 250 m^3 d^{-1} in 2004 [11], showing drastic effects to the nearby coastal environment, especially coral reefs and mangroves.

Fig. 2 Manado City with North Sulawesi Province [12]

Leading to the waste discharge, the production of waste is increasing from 828 $m^3\ d^{-1}$ in 2011 to 980 $m^3\ d^{-1}$ in 2014 [13]. In 2015, potential waste of the city was estimated about 1037 $m^3\ d^{-1}$ (assumption of 0.0025 $m^3\ ind^{-1}\ d^{-1}$) [14, 15]; up to 984 $m^3\ d^{-1}$ could be treated by waste dumping as the final destination of the waste, but about 52 $m^3\ d^{-1}$ were calculated to be released to the environment [14]; this could be end up into Manado Bay. The overall waste production in 2015 of North Sulawesi Province was 391,000 ton $year^{-1}$ [16]. In addition, in Bunaken Island, about 21–45 and 50–63% of wastes were in organic and inorganic forms, respectively. Most of the inorganic waste was attributed to tourism activity on the island [17].

After the local government of Manado released the regulation n. 7 in 2006, the management is officially regulated by the government. Since then however, significant changes have not been achieved yet. In fact, most of wastewater discharges occur with insufficient treatments [11] or even without any treatment at all [18].

This causes rivers flowing to Manado Bay through the city being full of garbage, especially long-lasting plastic waste.

There is a wide range of environmental impact due to insufficient management of inland waste and marine debris, especially plastic waste. Based on a survey by Green Eye Project Aquamarine Fukushima, Japan, in 2011, using ROV, they found large amounts of plastic trash on the bottom of Manado Bay and its surrounding area, close to Bunaken National Park (BNP). The assumed source of the trash was mostly from the inland area brought in through six rivers that flow across the city to the bay.

In Indonesia, plastic debris was found in the gut of about 20% of commercially caught fish, this being a drastic proof the Indonesian marine waters are polluted, mainly due to garbage [19]. As an accidental finding, there was the high gut content of plastic in the specimen of "living fossil" *Latimeria menadoensis*, the iconic coelacanth in 2012. This paragraph summed up the first collection of available information for this region.

2.2 *Best-Practice Environmental Activities*

In MC, in order to overcome this poor environmental condition due to plastic debris, all stakeholders (communities, students, civil servants, army, etc.) are mobilized to do best-practice environmental activities. One of the activities which are being conducted regularly is beach clean-ups. These events are also seen as a manifestation of community awareness to this problem. Such activity is being conducted not only at the city level of Manado but also at the provincial level of North Sulawesi. Moreover, such activity is regularly conducted within the CT countries through the Coral Triangle Day Program [20].

In Indonesia, other best-practice environmental activities are being conducted. In Manado, to manage the general waste, on-site composting of organic waste is conducted by each individual and/or by groups of the community which was initiated by themselves. This form of waste treatment is also the most common in the island of Bunaken [17]. In Bali, participation in waste management is conducted by community on a sociocultural base through a community-based waste management [3].

3 Experiences from Waste Management in the Mediterranean Sea

The Mediterranean Sea also has a high biodiversity, parts of which are already lost or highly threatened. Plastic pollution has a long history, and the problem has been addressed by large only recently. The Coral Triangle could profit from expertise and concepts developed in the Med and give in change experiences from a region where due to the relative short history of plastic waste, and still spatially restricted heavy urbanization, the impact on near-pristine marine ecosystems can be studied in order to find global solutions.

4 Further Actions

4.1 Indonesia Actions

Many actions are being conducted as countermeasures to the plastic debris pollution in Indonesia. On the local level of Manado City, it was advised to invest more in prevention, like proper education about the effects of garbage [11]. In 2004, key management strategies were proposed; they were private sector involvement; public awareness, cooperation and participation; and cost recovery and financial resources [21]. On the national level, the Presidential Instruction n. 12, 2016, was published as the direction for the Clean Indonesia Program. Based on this instruction, an action plan "the Indonesia's Plan of Action on Marine Plastic Debris 2017–2025" [8] was launched. The action recommended three important key aspects in handling marine plastic debris in Indonesia, such as coordination between institutions; application of technology to control plastic debris, including the application of science-based management; and the significant importance of societal efforts to reduce, recycle and reuse plastic debris to be advanced since early stage. The expected goal of this action is to reduce marine plastic debris by 70% in 2025.

In addition, in order to create countermeasures among the CT countries, a joint activity of Coral Triangle Initiatives (CTI) could be conducted. The CTI is a multilateral partnership of six countries (Indonesia, Malaysia, Papua New Guinea, the Philippines, Solomon Islands and Timor-Leste), located in the CT region and formed in 2007 to address the urgent threats faced by the coastal and marine resources of one of the most biologically diverse and ecologically rich regions on Earth [20].

4.2 Global Actions

Since marine debris does harm many marine organisms and wildlife [1, 22–24], global and local governance responses are needed to effectively manage the plastic marine litter problem [25]. Besides, joint actions and exchange of knowledge should lead to an efficient global strategy.

5 Final Remarks

An interdisciplinary action plan for the Manado area should be formulated that can be extended and adapted to the wider region of the Coral Triangle.

A quote from a biodiversity researcher and colleague: "*I really hope that some of the marine debris problems in Bunaken Island are addressed by the authorities in near future, or the island will be considered as another lost paradise*" (Waegele, 2016 pers.comm.).

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INDEKS

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TENTANG BUKU INI: Informasi tentang hasil penelitian dan pemantauan sampah laut Teluk Manado disajikan. Hasil penelitian yang disajikan meliputi kuantifikasi komposisi, kepadatan, dan berat sampah laut, status, dampak, kesadaran lingkungan masyarakat, dan penataan kelembagaan sistem pengelolaan sampah laut di Kota Manado. Hasil pemantauan yang disajikan meliputi pemantauan sampah laut di Teluk Manado pada bulan Agustus dan November 2020.

Buku ini diperuntukkan bagi para peneliti, pemerhati lingkungan, pelaksana pengelolaan lingkungan, dan pengambil keputusan dalam upaya merencanakan kegiatan pengelolaan dalam mengatasi masalah sampah laut. Namun demikian, buku ini bisa menjadi bahan informasi bagi berbagai kalangan, khususnya para pihak dalam bidang pengelolaan lingkungan pesisir dan laut.

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