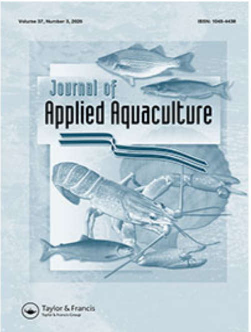

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The potential of textile substrates for the cultivation of marine macroalgae *Ulva* spp

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ABSTRACT

Technologies currently employed for land-based seaweed cultivation are cost-intensive and wasteful of resources. Hence, the present study examined natural and synthetic materials as growth substrates for a sustainable on-land production of *Ulva* spp. In total, 16 materials were qualitatively evaluated regarding their usability represented as availability, durability, reusability, and adherence, as well as growth of algae on the selected materials. The results of spore adhesion and mobility indicated that loofah sponge, clay pellets, and polyurethane foam were most suitable for algal adhesion. Synthetic materials generally exhibited low toxicity and high durability but low usability, as algal spores clogged the materials. In contrast, natural materials exhibited increased vulnerability to mechanical stress, leading to reduced durability and low reusability. Furthermore, toxic effects that might have inhibited movement and attachment of spores were more likely to occur from natural materials due to degradation processes during the tests.

KEYWORDS

Seaweed; macroalgae; on-land; land-based; cultivation, textiles

Introduction

As the vast majority of seaweed cultivation is conducted in coastal areas or offshore using longlines, nets, or artificial structures (Cai et al. 2021), it is highly threatened by climate change and the associated increased occurrence of diseases (Chojnacka 2011; Kilinc et al. 2013; López-Hortas et al. 2021). In light of the growing global demand for algal biomass, scientific efforts have to counteract the feared production losses by investigating possible procedural changes to reduce the limitations of existing cultivation processes (Buck and Buchholz 2004; Dinesh-Kumar et al. 2023; Holdt, Christensen, and Iversen 2014; Neori et al. 2020).

While the land-based cultivation of marine algae offers temporal and qualitative control of the production process and avoids undesired biotic and abiotic changes (Azevedo et al. 2016; Hafting et al. 2011), its use of

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cylindrical tanks, ponds, or raceways as cultivation methods has serious limitations that restrict their performance and possible applications (Abreu et al. 2009; Robertson-Andersson et al. 2008). Large quantities of culture medium have to be circulated, tempered, and cleaned to ensure a uniform light exposure and nutrient exchange and to avoid stagnation and dead zones (Abreu et al. 2009; Lüning and Pang 2003; Sebök, Herppich, and Hanelt 2017), which results in high costs. Alternatives like the co-cultivation of seaweeds as part of integrated multitrophic aquacultures or the development of a seaweed hatchery (Abreu et al. 2009; Robertson-Andersson et al. 2008) depend on seawater availability and its regular replacement, and are thus no solution to the problem.

An emerging new direction of research that intends to mitigate the already-mentioned problems focuses on the targeted growth of macroalgal spores on textile substrates and their subsequent development on those substrates (Ehrmann 2019). A successful cultivation on textile substrates would render large amounts of medium and tumbling unnecessary, which in turn would reduce costs and maintenance, while enabling better control of the production process (Johnson and Wen 2010). Of the few studies conducted to date that investigate alternative materials as growth substrates for marine macroalgae, nearly all exclusively focused on enhancing the production of seeding for seeding lines and ropes (Forbord et al. 2020; Jiksing et al. 2022; Kerrison et al. 2020; Kerrison, Stanley, and Hughes 2018). For example, wool (Drury and Crotty 2022) and synthetic yarn (Prakash and Viswanath 2019) were examined as alternative materials for seeding lines, while Visch et al. (2023) mentioned the negligible effect of a binder treatment of seeding ropes on the adhesion efficiency of gametophytes. However, data on other possible materials remain scarce.

Studies on algal adhesion are limited to microalgae and focus on finding technological solutions for an improved cultivation (Christenson and Sims 2012; Genin, Aitchison, and Allen 2013, 2015; Johnson and Wen 2010; Sekar et al. 2004). The only study on macroalgae in this context is by Sebök et al. (2020), who introduced a new approach using knitted textiles as an alternative growth substrate for the land-based cultivation of the macroalgae *Ectocarpus* sp. Criteria that have so far been identified to determine the choice of materials to be used as growth substrates are availability, reusability, toxicity, and adhesion (Deantes-Espinosa et al. 2019; Johnson and Wen 2010; Petersen, Gorb, and Heepe 2020; Schnurr and Allen 2015). However, these criteria were determined based on experiments on microalgae, while the ability of marine macroalgae to grow on substrates is still mostly unknown.

Therefore, this study intends to fill some of these data gaps by selecting a variety of natural and synthetic materials and testing their ability to act as a growth substrate for the marine macroalgae *Ulva* spp. on a semitechnical scale. The macroalga *Ulva* was used as it is one of the few local seaweed species in Germany that are used as food and for which there is a perceivable, rising demand as food or food supplement (personal communication, Viva Maris GmbH). In addition, *Ulva* is an opportunistic seaweed that grows extremely well in highly variable habitats (Bruhn et al. 2011). The selected materials were evaluated with regard to their usability—represented as the ability of algae to adhere to and grow on the substrate materials—their reusability, and to some extent their toxicity, expecting natural materials to prove more suitable as growth substrates. The results will form the basis for future studies aiming at the identification of suitable materials for a more sustainable production of seaweed on land.

Material & methods

Algal material used in the experiments

Experiments were conducted using spores of the fast-growing laminar marine green alga *Ulva lactuca* and the filamentous marine green alga *U. compressa*. Original seeding materials of both *Ulva* species were collected on the beach of List, Sylt, Germany (55° 34' N, 8° 25'O) in May 2023. The algal material was further proliferated under laboratory conditions to stimulate axenic seed culture according to Balar and Mantri (2020) and Niesenbaum (1988). Prior to the proliferation, the algal material was disinfected using 0.1% sodium hypochlorite solution for up to 5 min according to Kerrison et al. (2016). Sporulation was induced by manually cutting the thallus into pieces of approximately 1 cm^2 and applying a thermal shock of 20°C for 2 h and subsequently transferring the algal material into 5 L of artificial seawater overnight (Niesenbaum 1988; Wichard and Oertel 2010). Sporulation was confirmed by microscopic identification (Swift SS300B, SWIFT, Texas, USA) of spores in the liquid on the following day.

Preparation of culture medium

Algae were proliferated and cultivated using Provasoli enriched seawater (PES), which had been prepared with artificial seawater (ASW) based on distilled water and Tropic Marin salt (Tropic Marin, Dr. Biener GmbH, Wartenberg, Germany) to which Provasoli enrichment (PE) was added. The PE medium was prepared according to the recipe given by Andersen et al. (2005), which had been derived from ES medium (Provasoli 1966) and modified ES medium (McLachlan 1973). The PE medium used in the tests did not contain Tris buffer and was added in 10-fold concentration in order to avoid salinity decrease in the ASW. Salinity was measured every week using a digital refractometer (HI 9033, Hanna Instruments GmbH, Vöhringen, Germany) to ensure a constant salinity of 30 according to Bruhn et al. (2011).

Assembly of test setup

To evaluate the *Ulva* spores' growth behavior on different materials, a cylindrical tube (diameter: 20 cm, height: 100 cm) was placed into a larger cylinder made of acrylic glass (volume: 125 L, diameter: 40 cm, water height: 100 cm). The different materials were attached beneath each other on the inner cylinder's outer surface. After filling the acrylic glass tube with ASW, 500 mL of spore-enriched medium was added. After 24 h of cultivation, samples of the medium were microscopically analyzed to confirm spore mobility. Four light-emitting diode (LED) strips of 1 m length (Cosmorrow Grow LED PPE2.7, Secret Jardin, Manage, Belgium) were placed in front of the outer acrylic glass cylinder on both sides at a 45° angle, providing an average photosynthetically active photon fluence rate (PFR) of 150 µmol m^{-2} s^{-1} at a light-dark cycle of 14 h:10 h (IP65, Mean Well Enterprises Co. Ltd, New Taipei City, Taiwan). Using a light meter (LI-1400, LI-190 R, Li-Cor, USA), the PFR of 150 µmol m^{-2} s^{-1} was measured at the beginning of the experiments at the inner cylinder's outer side. The culture medium was not replaced during the 30 d of the experiment. The temperature was kept constant within the temperature range of 13.0 ± 1.0°C (Frost-Christensen and Sand-Jensen 1990) using a water chiller (Hailea HC-250A, Raoping, Guangdong, China). To provide water movement and tumbling of algal material, a centralized air injector (Hailea HAP 100, Raoping, Guangdong, China) was used, releasing approximately 3.4 m^3 h^{-1} of air at a water column of 1 m. PE was provided as nutrient supply at 50% of the regular concentration (Berges, Franklin, and Harrison 2001). At the beginning and end of every testing period, microscopic images of the surface of each piece of fabric were taken at magnification levels of up to 40 × (MikroCam SP5.0, Bresser GmbH, Rhede, Germany) to evaluate structural changes of the substrate and the growth and attachment of the algaeto the fabric. On the second and fourth day of each experiment, the culture medium was microscopically analyzed (Swift SS300B, SWIFT, Texas, USA) to control mobility of algal spores. Each fabric was tested thrice using three identical test setups (cylinder setup) in which each specific material was tested simultaneously.

Test setup for control group

In addition to tests using the cylindrical tube, accompanying investigations were carried out using low basins (volume: 2 L, material: polypropylene, size: 30.0 cm × 21.0 cm). These tests were used as control approach to eliminate a possible effect of the experimental design on the growth of algal spores on the materials. The experiments with basins used light, temperature, and nutrient conditions similar to those of the tests in the cylindrical tube. Each individual material was placed on the bottom of the basin, and 1.5 L of cultivation medium as well as 100 mL of spore-enriched medium were added. A centralized glass tube connected to an air injector (Hailea ACO 208, Raoping, Guangdong, China) provided sufficient water movement in the basin. Microscopic images of the surface of each piece of fabric were taken after the test duration of 30 d. Each material was tested in duplicate using two basins per material.

Methods used for characterization of textile fabrics

The thickness of the investigated textile fabrics and other substrates was measured with the digital thickness gauge for textiles and nonwovens J-40-T (Wolf-Messtechnik GmbH, Freiberg, Germany) according to ISO 5084. Sample masses were taken with an analytical balance VWR LA Classic (VWR International GmbH, Darmstadt, Germany). For the investigation of the mass per unit area (abbreviated as areal weight), circles of 100 cm^2 were cut from the textile samples, or rather rectangles in case of sturdier materials, and the area was weighed.

Description of tested textile fabrics

Textile samples with dimensions of approximately 20 cm × 10 cm were provided by different producers and produced through different textile technologies. Of the 16 fabrics used in the experiments, 9 materials were synthetic, 5 natural, and 2 of a combined synthetic and natural kind. Characteristics of fabrics are described in Table 1.

Parameters for assessing growth substrates

The parameters availability, reusability, toxicity, and adhesion were selected to assess the materials' usability as macroalgal growth substrate. All 16 materials were selected by a third party (Texulting GmbH, Dresden, Germany) according to the general subdivision into synthetic materials, natural, or combined synthetic and natural materials and considering the materials already analyzed by Ehrmann (2019) and Sebök et al. (2020).

Availability was defined as a measure of the general possibility to retrieve the materials cost-effectively, in theoretically large quantities and without delay and without custom fabrication (Gross et al. 2016). In addition, availability of a material also concerns the material's technological and economically viable manufacturability under consideration of the additional costs of customized production. A fast, cost-effective supply of the material, in particular, without the need for customization was thus considered advantageous, whereas an expensive and custom-fabricated material was negatively assessed.

Table 1. Material description, producer of materials, and thickness, areal weight, and nature of textile used in the present study.

No.	Material and textile structure	Producer (country)	Thickness (mm)	Areal weight (g*m^{-2})	Synthetic (S), natural (N), or combined (C) fabrics
1	Inbitex nonwoven membrane made of polypropylene and polyethylene mixture	Geotextile Membranes Inc. (UK)	0.7	105	S
2	Expanded clay (grain size of 8–20 mm) attached on high-density polyethylene (HDPE) leno fabric with mesh size of 10 mm	LECO-Werke Lechtreck GmbH & Co. KG; Fibo ExClay Deutschland GmbH (GER)	25.1	3575	C
3	Large spacer fabric made of polyethylene terephthalate (PET)	Eschler Textil GmbH (GER)	22	957	S
4	Nonwoven viscose fabric	Kelheim Fibres GmbH (GER)	2.1	172	S
5	Woven coir net made of 100% two-ply coir fibers with tread space of 10–15 mm	Internationale Geotextil GmbH (GER)	7.3	809	N
6	Needle felt nonwoven made of polypropylene and polyethylene terephthalate (PET)	Polytec Kunststoffverarbeitung GmbH & Co. KG (GER)	7.3	822	S
7	100% Straw blanket stitched with jute thread	Internationale Geotextil GmbH (GER)	10.9	835	N
8	100% Coir blanket stitched with jute thread	Internationale Geotextil GmbH (GER)	5.9	457	N
9	Blanket made of 100% polyamide fibers	Aquagart Trading GmbH (GER)	17.6	290	S
10	Polypropylene blanked with stones (grain size of 8–20 mm) attached	Aquagart Trading GmbH (GER)	4.7	4010	C
11	Loofah sponge material	Plantish Future Inc. (USA)	4.2	560	N
12	Flocked polyamide blanket (see no. 9)	Aquagart Trading GmbH (GER), Texulting GmbH (GER)	20	290	S
13	Basalt fiber mat	Basalt Fibertec GmbH (CH)	8.07	1170	N
14	Polyurethane foam material	JBL GmbH & Co. KG (GER)	10.9	269	S
15	Small spacer fabric made of 100% polyethylene terephthalate (PET)	NetzfabrikRudolf Baumbach GmbH (GER)	3.7	361	S
16	Weft-knitted tuck-plush (polyamide)	Unknown	7.1	385	S

Reusability as a criterion was defined as a material's capacity to be used multiple times without visible degradation or structural change of the material itself, which requires the material to have a certain degree of durability as a function of sturdiness and flexibility according to Venable and Podbielski (2019) and Moreno-Osorio et al. (2021). Reusability also considered the necessary level of cleaning the substrate before reusing. Hence, a durable material that neither changes its structural conditions nor requires maintenance was considered advantageous.

Toxicity was defined as the effect of a tested material or its chemical compounds impairing or inhibiting the mobility of algal spores (Briand 2009). For this purpose, the mobility of *Ulva* spores in the culture medium was microscopically analyzed on days 1, 2, and 4 after the start of each experiment. Materials that did not affect spore mobility after 2 and 4 d into the experiment were considered advantageous.

Adhesion was defined as the number of algal spores that successfully attached to the substrates and started growing. Although surface chemistry and surface topography are the two main material properties influencing adhesion success, no consensus was found in the literature regarding the quantifiability of each parameter (Finlay et al. 2008; Petersen, Gorb, and Heepe 2020; Schnurr and Allen 2015; Sekar et al. 2004). Hence, adhesion was solely determined by the growth of algal spores on the substrate after the testing period of 30 d.

Results

Table 2 shows images of the different materials used as growth substrates for *Ulva* spores before and after the testing period. The following paragraphs describe the findings after the testing period regarding the usability of each material as a possible growth substrate. Material 1 (Inbitex nonwoven membrane made of polypropylene and polyethylene mixture) was selected due to its structure with high roughness combined with high stability. The recognizable individual fibers were expected to serve as an adhesive base for the algal spores to settle and adhere to. After the 30-d testing period, the material was found to be a poor candidate as a growth substrate for *Ulva* spp. Penetration and adhesion of spores to individual fibers hardly occurred. Algal spores were found to adhere only to detached individual fibers. During the testing period, material 1 remained stable and can therefore be described as being reusable.

Material 2 (expanded clay attached to HDPE leno fabric) was selected as a growth substrate due to the visible porosity of the clay pellets, as it was assumed that a porous structure would achieve good attachment of the algal spores. Preliminary tests with bonded clay pellets and *Ulva* spores assessing the possible toxicity of the used adhesive showed complete immobility of the algal seed material after 4 h. To reduce the suspected spore-inhibiting effect of the adhesive, the material was soaked repeatedly in fresh water. However, this caused the clay pellets to detach and the entire material to float. These results suggest that this material's usability as a growth surface is limited. The growth tests showed that the clay pellets can serve as an excellent substrate. Visible growth of *Ulva* happened on all areas of the clay pellets that were facing the light. The increasing size of the growing algae caused a second detachment of the clay pellets from the underlying net structure, presumably due to the fact that the overgrown clay pellets caused an increased flow resistance compared to the uncovered clay pellets, which led to the detachment.

Material 3 (large spacer fabric made of polyethylene terephthalate (PET)) was a loose, porous spacer fabric and was used in two different forms. On the one hand, the knitted fabric remained unchanged (material 3a), and on the other hand, it was cut in half lengthwise and attached to the inner tube of the test setup with the cut side facing outward (material 3b). The results of the

Table 2. Images of different materials before and after testing as growth substrate for *Ulva* over a testing period of 30 d in a cylindrical tumble culture.

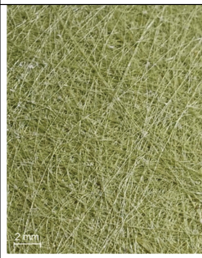
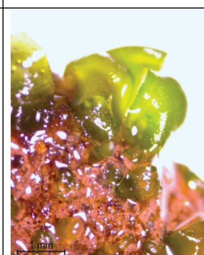
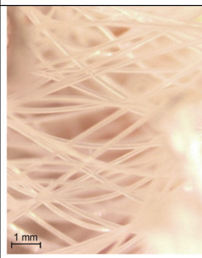
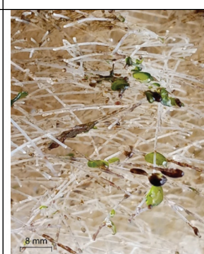
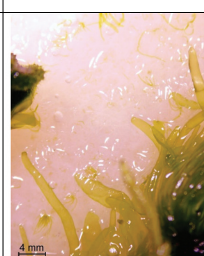
Number of material	Image of material before testing (without magnification)	Image of material before testing (10 x magnification)	Image of material after testing (without magnification)	Image of material after testing (10 x magnification)
1				
2				
3				
4				

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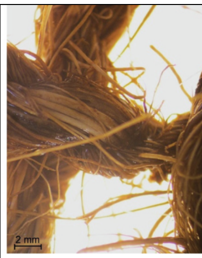
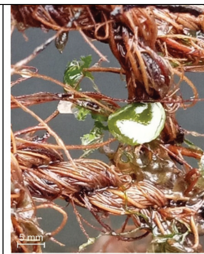
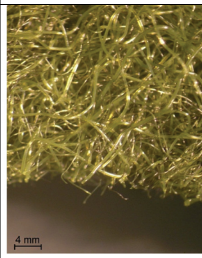
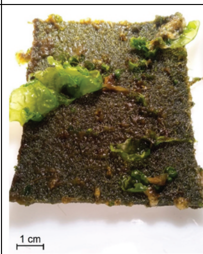
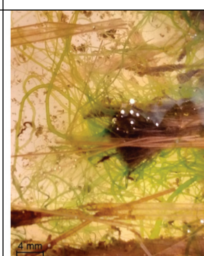
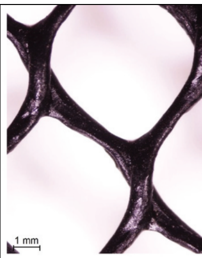
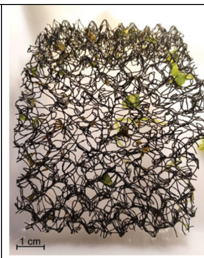
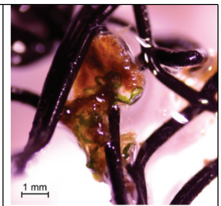
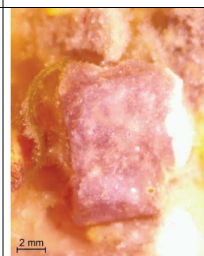
Table 2. (Continued).

5				
6				
7				
8				

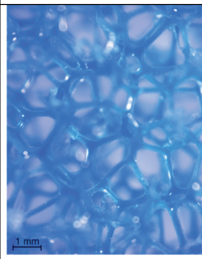
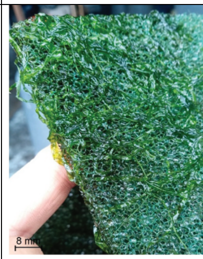
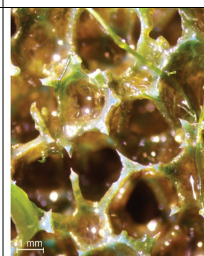
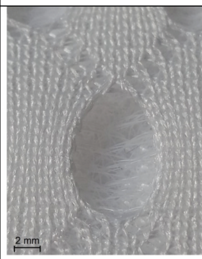
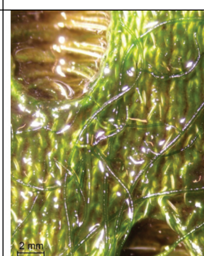
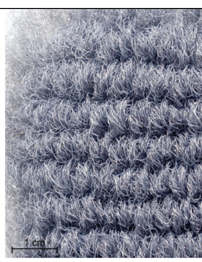
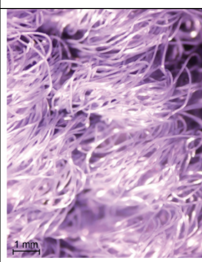
(*Continued*)

Table 2. (Continued).

9				
10				
11				
12				

(*Continued*)

Table 2. (Continued).

13				
14				
15				
16				

tests with both variants were similar. Adhesion of the *Ulva* spores to the smooth monofilaments inside the knitted fabric was hardly detectable. On the outer side, *Ulva* spores were found to adhere to and grow in several places. In terms of reusability, the material must be classified as difficult: Both algal spores and algal material got caught in the internal monofilament structure and degenerated there, making it necessary to manually clean the fabric before reuse.

Material 4 (nonwoven viscose fabric) was chosen due to its loose arrangement of fibers. It proved to be conditionally useable as a substrate for adhesion of *Ulva* spores. The material had a recognizably loose structure, which was assumed to be favorable for spores to adhere. After the 30-d testing period, only a little growth could be detected on the material. In many cases, the growth was concentrated on the edges, where, due to cutting, the material structure showed a high degree of fraying. Nevertheless, there were also isolated spots of adhesion in the central area of the textile. The adhesion of algae can be described as stable. The material was easily cleanable; however, algae adhering to the inside of the textile required intensive cleaning.

Material 5 (woven coir net) represented a loose, fiber-rich net structure, leading to the assumption that the numerous individual fibers could serve as a promising adhesive base for algal spores. The growth tests showed that the material was hardly used as an adhesive structure. After the 30-d testing period, the mesh structure was almost completely free of any algal growth. A preliminary test using material 5 and *Ulva* spores to test for a possible inhibitory effect showed that algal spores were still mobile after 4 h. It can be assumed either that a release of inhibiting organic substances by the material took place over a long-term period or that the material properties are not suitable as a growth structure for *Ulva* spores.

Material 6 (needle-felt nonwoven made of polypropylene and polyethylene terephthalate (PET)) was an open-meshed nonwoven with a fiber-rich structure and high stability. The growth tests over 30 d showed adhesion to and growth of the algal spores on the material. The growth was evenly distributed over all areas of the textile. The algal thalli could be removed easily at the end of the tests without any damage to the textile. Neither the assumed increased shear stress caused by growing algal thalli in the textile nor the salinity of the culture medium caused any detectable damage to the textile.

Material 7 (straw blanket) was a mat made of a jute knit filled with loose straw pieces with a measurable length of approximately 4–12 cm ($n = 15$). The investigation of the adhesion and growth of algae on material 7 showed an early disintegration of the straw mat due to air injection in the cultivation tank. Algal spores adhered almost exclusively to the cutting areas or broken areas of the straw pieces and not to their longitudinal areas. In addition, there was growth on the jute holding structure. The straw mat can be excluded from the list of possible substrates, as it was not possible to remove the algae from the straw pieces without causing lasting structural damage to the whole mat. Furthermore, the disintegration of the mat during the testing period made a reutilization impossible.

Material 8 (coir blanket) was a mat made of loose coir fibers that were held in place by a jute knit. The coir fibers were supposed to serve as an adhesive base for the algal spores. The tests showed a lack of growth and adhesion similar to material 5 (woven coir net). Growth was only detectable on few of the jute strands, however, not on the coconut fibers. The use of material 8 as growth substrate must be discarded as the material disintegrated due to the air injection in the cultivation tank, leading to a visible decomposition of the fixing jute strings during the course of the growth test.

Material 9 was an open-pored plastic-based grid structure, which was chosen due to the assumed favorable perfusability, leading to a low flow resistance. As the growth tests with algal spores showed no obvious colonization by *Ulva* spp., it was assumed that this was due to a lack of roughness. After the end of the testing period, however, it became apparent that the material had been frequently colonized by algal spores but the spores had not grown into adult thalli. It was assumed that the low flow resistance of the material offered no protection for the spores to grow thalli. Parallel experiments with spores of the species *Saccharina latissima*, however, showed adhesion of the algal spores and initial growth (Figure 1).

Material 10 (polypropylene blanket with stones attached) was selected, as it was assumed that stones are a natural growth substrate for algal spores. However, the tests with algal spores did not lead to any successful growth. A toxicity test of the material, carried out after the growth test, showed a rapid inhibition of the mobility of the algal spores after approximately 2 h. It can be assumed that the adhesive that was used to attach the stones on the polypropylene blanket caused this inhibitory effect, making the material unsuitable as a growth substrate.

Material 11 (loofah sponge) was used as a third purely plant-based growth alternative that can be obtained at low cost and is commonly used in wet areas.

Figure 1. Successful attachment of *S. latissima* spores on tested material 9.

Growth tests over a period of 30 d with *Ulva* spp. showed good adhesion of the spores and subsequent growth of the thalli on the material. All tests showed a colonization of the whole area exposed to light. Nevertheless, a partial breakup of the material was observed on days 20 to 23, followed by its complete disintegration at the end of the testing period. In terms of its reusability and durability, the material was thus classified as unsuitable.

Material 12 (flocked grid) was based on material 9, which, after the application of a water-based dispersion adhesive, was electrostatically flocked using polyamide fibers as flock. The aim of the flocking was to increase the available surface of the material, which was supposed to have a favorable effect on the adhesion and growth of algal spores. Although the growth tests showed that the *Ulva* spores successfully adhered to the flocked material, after the testing period the flocking was found to have come off, particularly in the outer area of the flocked material. The detachment of the flocking was probably due to the circulation of the medium and the water current, which in turn resulted in the loss of the algal spores adhering to the material. While the flocking mostly remained in core areas of the material and the algal spores were able to grow into larger thalli, the manual removal of these thalli after the testing period led to the destruction of the flocking. Due to the instability of the flocking, material 12 thus has to be categorized as unsuitable for reuse.

A basalt fiber mat was used as material 13. It was made from basalt rock, a natural volcanic rock that is processed into fine fibers by melting and subsequent stretching. The resulting fibers are then shaped into a mat and fixed together. After the testing period of 30 d no attachment of algal spores or growth of algae on the material could be detected. A preliminary soaking of the material to eliminate possible toxic substances did not yield a different result. The material itself remained unchanged after exposure to the tumbling in the cultivation tank and the salinity of the culture medium.

Material 14 (polyurethane foam material) was a chemically inert, open-pored material with presumed good flow properties and long-term stability due to its synthetic nature, as it is widely used as a filter material in aquariums. The growth tests over a period of 30 d showed stable adhesion of the algal spores and growth that was evenly distributed over all areas of the textile. After the 30-d testing period, the algal thalli were easily removed and the textile could be cleaned effortlessly without damage to the material. In terms of reusability and adhesion, the material can thus be classified as suitable.

Material 15 (small spacer fabric made of 100% polyethylene terephthalate (PET)) was a pore-rich spacer fabric. The growth experiments showed an adhesion of *Ulva* spores on the outside (fabric side), while no adherence or growth was detected on the smooth monofilaments inside the knitted fabric. With regard to reusability and adhesion, the material is to be classified as difficult, as detached algal material got caught in the internal monofilament structure and degenerated. Hence, cleaning the material is laborious.

Material 16 (weft-knitted tuck-plush) was a densely knitted plush fabric that exhibited reduced circulation during the testing period, thus providing favorable conditions for the adhesion and growth of algal spores. The spores adhered mainly to the cutting edges of the fabric but also, though less frequently, to the center of the material. The thalli were firmly attached to the material. The removal of attached algae was effortless and cleaning the material caused no damages to it.

Discussion

The use of textile growth surfaces for the cultivation of seaweed holds high optimization potential despite the disparate results of this study. However, scientific research of textile growth surfaces for algae cultivation remains limited, particularly with regard to seaweed and land-based cultivation approaches of macroalgae. Existing data are primarily drawn from studies using microalgae, which differ significantly in adhesion behavior and substrate interaction. Consequently, the cultivation parameters established for microalgae can only be transferred to macroalgae to a limited extent. In addition, the lack of clearly defined and quantifiable parameters also limits the transferability of conclusions regarding the useability of textile substrates for macroalgal production.

Following Schnurr and Allen (2015) as well as Deantes-Espinosa et al. (2019), the identified criteria for growth materials included availability, reusability, toxicity, and adhesion. Availability of a material was not limited to the accessibility of a substrate's raw materials but rather referred to the material's technological and economically viable manufacturability under consideration of the additional costs of customized production (Gross et al. 2016). Although all tested materials were technically available, they exhibited considerable differences in the economic viability of their purchase or production, as for example the production of expanded clay pellets attached to HDPE leno fabric (material 2).

The criterion of reusability, or recyclability, examines the sturdiness and durability of the materials under the conditions of the saline medium and the cultivation process (Gross et al. 2016; Venable and Podbielski 2019). Most of the synthetic materials (except materials 2 and 12) exhibited a high sturdiness and durability, as neither salinity nor turbulence affected the integrity of the materials and no visible biodegradation took place (Ehrmann 2019; Venable and Podbielski 2019). However, in the case of materials 2 and 12, which were custom fabricated, the turbulence in the cultivation process led to a visible disintegration or abrasion of the materials, respectively, while the saline medium was without effect on the material during a 2-month parallel test. The organic materials exhibited a wide range of behaviors. Materials 7 and 11 were highly affected by the saline medium and/or the shearing stress of the cultivation process and showed visible deterioration after the 30-d testing period, while material 8 was more durable and did not show any signs of degradation until after 60–70 d. It seems that although organic materials might be environmentally friendly, the materials' biodegradation will increase operation downtime, reducing productivity and causing additional costs as they require frequent replacement (Gross, Jarboe, and Wen 2015).

Regarding toxicity, growth tests showed that some organic materials (e.g., materials 5, 7, and 8) as well as a few synthetic materials (e.g., materials 10 and 13) might contain toxic or inhibiting substances that caused a fast inhibition of spore mobility (Kobetičová et al. 2022). This, in turn, led to a reduced adherence yield and a decreased growth of algae on the materials, similar to the findings of Wichard and Oertel (2010) and Deantes-Espinosa et al. (2019), or, following Irving and Allen (2011) and Moreno-Osorio et al. (2021), negatively affected the formation of microalgal biofilm, which inhibited the adherence of *Ulva* spores to the substrates. A special case might be material 2, which also showed a fast inhibition of spore mobility. Here, it had been assumed that it was not the expanded clay but rather the adhesive that attached the expanded clay to the carrier substrate HDPE leno fabric or the HDPE leno fabric itself that might have caused the detected inhibition of adherence and reduced growth of the spores by gradually releasing toxic substances into the cultivation medium (Wind et al. 2022). Similar results of inhibiting adhesion and growth of algal spores were found in Briand (2009), Balar and Mantri (2020), and Wichard and Oertel (2010). In case of material 2, the preliminary soaking of the expanded clay pellets attached to the carrier substrate over a time period of multiple days showed no improvements of the adhesion yield, which rather supports the assumption of a gradual release of inhibiting substances. It became obvious that the issue of possible material toxicity has to be given more attention. In-depth analyses of material components and preliminary leaching tests have to be included in test setups and budget planning.

The adhesion criterion, that is, the number of algal spores that successfully attached to the substrates and started growing (Christenson and Sims 2012; Genin, Aitchison, and Allen 2013), was determined by two main material properties: surface chemistry and surface topography. As there seems to be no consensus in the literature regarding an accurate definition and, in fact, terms for these properties, for the purpose of this article, "surface chemistry" encompasses the parameters of wettability (Petersen, Gorb, and Heepe 2020; Sekar et al. 2004), hydrophobicity (Moreno-Osorio et al. 2021; Sekar et al. 2004), contact angle (Cui, Yuan, and Cao 2013; Gross et al. 2016), and surface energy (Gross et al. 2016; Moreno-Osorio et al. 2021) of a material as they are defined in the respective literature, while "surface topography" refers to the roughness (or texture) on a macroscopic and microscopic level (Cui, Yuan, and Cao 2013; Genin, Aitchison, and Allen 2013; Schnurr and Allen 2015; Schumacher et al. 2007; Sekar et al. 2004). Therefore, due to the inaccurate definition of the quantitative parameters in combination with their problematic measurability on rough/uneven surfaces, a general approach of measuring attached spores to assess the adhesion was used.

Furthermore, although the majority of existing research on these material properties was done with microalgae, this article follows Gross, Jarboe, and Wen (2015) in their assumption that dependencies similar to those observed for microalgae might be valid for the adhesion of macroalgal spores. In terms of adhesion success, the growth test within this study showed inconclusive results regarding possible advantages of organic or synthetic materials, respectively. Independently of the parameters availability, reusability, and toxicity, the adhesion behavior of algal spores was best on the organic material 11 and on the synthetic materials 6 and 14. As Gross et al. (2016), Chaudhury et al. (2005), and Cao et al. (2009) explained, an increase of the surface roughness creates areas where the velocity of the culture medium is reduced, so algal cells have enough time to settle on the surface and subsequently adhere to it. The assumption that the highly texturized materials 6 (clay pellets), 11 (loofah sponge), and 14 (polyurethane foam) would provide beneficial environments to the successful settlement of *Ulva* spores was confirmed by the test results in Table 3.

There are indications that, in addition to the described properties of the materials, the adhesion success of algae might also depend on the parameter color (Finlay et al. 2008) and on the formation of an extracellular polymer substance (EPS) as biological structure (Boizard 2007; Leupold et al. 2013; Moreno-Osorio et al. 2021; Nachtigall 2013). Finlay et al. (2008) described that

Table 3. Summarized assessment of tested materials regarding parameters availability, reusability, toxicity, and adhesion; "+" represents high; "0" represents inconclusive; "-" represents low.

No.	Material and textile structure	Availability	Reusability	Non-toxicity	Adhesion
1	Inbitex nonwoven membrane made of polypropylene and polyethylene mixture	+	0	+	0
2	Expanded clay (grain size of 8–20 mm) attached to HDPE leno fabric with mesh size of 10 mm	0	–	–	+
3	Large spacer fabric made of polyethylene terephthalate (PET)	+	–	0	–
4	Nonwoven viscose fabric	0	+	+	+
5	Woven coir net made of 100% two-ply coir fibers with tread space of 10–15 mm	+	0	–	–
6	Needle-felt nonwoven made of polypropylene and polyethylene terephthalate (PET)	+	0	+	+
7	Blanket made of 100% straw stitched with jute thread	+	–	+	–
8	Blanket made of 100% coir stitched with jute thread	+	–	+	–
9	Blanket made of 100% polyamide fibers	+	+	+	–
10	Polypropylene blanket with stones (grain size of 8–20 mm) attached	+	+	+	–
11	Loofah sponge material	+	–	+	+
12	Flocked polyamide fiber blanket (see no. 9)	–	–	0	–
13	Basalt fiber mat	–	+	0	–
14	Polyurethane foam material	+	0	+	+
15	Small spacer fabric made of 100% polyethylene terephthalate (PET)	+	0	+	+
16	Weft-knitted tuck-plush (polyamide)	+	+	+	+

the coating color of the material can have a profound effect on the growth, size, and strength of attaching *Ulva* spores. However, as this information was not known before the test and thus, the test setup did not account for this possible influence. The germination and development success of *Ulva* spores as well as differences in growth and strength of attached algae might be partially attributed to the material color. Regarding the formation of biological structures (EPS), it was shown for microalgae that the development of an EPS on the material can improve and stimulate the adhesion (Cui, Yuan, and Cao 2013; Moreno-Osorio et al. 2021; Schnurr and Allen 2015). However, it is largely unknown which strategy is relevant for a colonization of growth surfaces by macroalgae. Hence, the development and influence of an EPS might also be a basic prerequisite for a successful adhesion of macroalgal spores.

As synthetic materials performed better than expected, the problem of microplastics must be addressed. If microplastics are found to leach into the cultivation medium, appropriate steps have to be included in the filtration process of the medium. Preliminary studies showed that filamentous algae have the capacity to remove 44% of the suspended micro- and nanoplastics with their biomass (unpublished results). If microplastics can enter the algal biomass, the use of the respective synthetic materials themselves has to be suspended until safe materials with similar characteristics can be produced. Although it would be preferable to avoid the issue of microplastics by restricting the selection of growth substrates to organic materials, these materials showed an increased vulnerability to the mechanical stress and salinity of the cultivation process.

In addition, the question of quantitative data should also be considered, as this study has shown that the existing qualitative parameters, which are primarily used for microalgae, can only be used to a very limited extent to quantify the growth success of macroalgae.

Conclusion

The intention of this study was to identify suitable materials based on their ability to act as a growth substrate for land-based cultivation of the marine macroalgae *Ulva* spp. Growth tests using *Ulva* spores and different synthetic and organic materials showed disparate results regarding the parameters availability, reusability, toxicity, and adhesion. The parameters availability and reusability were found to be interrelated with the economic feasibility of the material. Although synthetic materials mostly proved to be more durable, their reusability was not guaranteed due to their thicker construction and potential function as a sieve element, which led to high maintenance costs due to the necessity for thorough cleaning. Thus, in terms of economic viability, availability should be considered the main criterion for assessing growth materials. With regard to toxicity, it was demonstrated that both organic and synthetic materials may contain toxic or inhibitory substances, which resulted in an inhibition of spore mobility and a reduction of the adherence yield. Regarding the adhesion quality of synthetic and organic materials, the relevant properties of surface chemistry and surface topography could not be clearly identified. Test results substantiated the assumption that clay pellets, loofah sponge, and polyurethane foam represent the materials with the most beneficial conditions for the adhesion and growth of *Ulva* spores. Apart from developing new quantitative methods for the evaluation of textile substrates and the potential problem of microplastics, future research should address the possibility that different growth materials might be favorable for different seaweed species, and eventually face the issue of large-scale applications. In addition, subsequent research should address the color of the tested material, or consider a standardized color for all materials, as well as the factor of EPS formation. This is because both color and EPS may influence the adhesion efficiency of the selected seaweed and the performance of the tested material.

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Data availability statement

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

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