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On the Possible Use of Textile Fabrics for Vertical Farming
O možnostih za uporabo tekstilnih materialov za vertikalno kmetovanje

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Abstract
Vertical farming is one of several ideas that are being developed further by diverse research groups, companies and private citizens. Due to the growing problems of urbanisation and a growing population, vertical farming has presented itself as one possibility to feed people, particularly in large and densely crowded cities, in an efficient and eco-friendly way. Interestingly, while agrotextiles are often used in agriculture and textile fabrics can be bought, for example, as frames for small vertical farming solutions for private balconies, only a few researchers have studied the possibilities of using textile fabrics as substrates for vertical faming to date. This study provides an overview of possible future applications of textile fabrics in vertical farming solutions.
Keywords*:* vertical farming, vertical gardening, textile fabrics, agrotextiles, plants, algae, hydroponics, aeroponics, aquaponics

Izvleček
Vertikalno kmetovanje spada med ideje, ki jih razvijajo različne raziskovalne skupine, podjetja in zasebniki. Zaradi naraščajočih problemov urbanizacije in rasti svetovne populacije je vertikalno kmetovanje lahko ena od možnosti učinkovitega in okolju prijaznega načina zagotavljanja hrane, zlasti v velikih in gosto naseljenih mestih. Zanimivo pa je, da se kljub temu, da se agrotekstilije pogosto uporabljajo v kmetijstvu in da so na trgu na voljo tekstilni materiali za okvirne rešitve vertikalnega kmetovanja za zasebne balkone ipd., le manjše število raziskovalcev ukvarja z možnostjo uporabe tekstilij kot substrata za vertikalno kmetovanje. Članek predstavlja pregled možnosti za uporabo tekstilnih materialov za vertikalno kmetovanje v prihodnosti.
Ključne besede: vertikalno kmetovanje, vertikalno vrtnarjenje, tekstilne tkanine, agrotekstilije, rastline, alge, hidroponika, aeroponika, akvaponika

1 Introduction

According to the latest World Population Prospects, the world's population will grow continuously over the next decades [1]. Fighting hunger and malnutrition will become even more difficult than it is today, particularly in the poorest countries where population growth is expected to be highest [2]. Even in wealthier countries, however, total agricultural land area is frequently insufficient to cover the demands of the population for food. For example, a recent statistical report indicates a demand of $18.3 \cdot 10^6$ ha for food production in Germany for 2016, while only $14.0 \cdot 10^6$ ha of the total available agricultural land area of $16.7 \cdot 10^6$ ha were used for food production. The missing food, corresponding to the difference of $4.3 \cdot 10^6$ ha, was bought abroad [3].
This is one of the reasons why vertical farming is of major interest in research and development. The main idea of vertical farming is to grow vegetables

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or other plants vertically, typically inside of high buildings. One possibility is to have several floors (or thinking on a smaller scale, several levels in a large shelf-like structure) that are used for farming. Water is often transported from the highest levels down to the next levels until it reaches the lowest level and is pumped back to the highest level, ideally achieving a closed water recycling system. On the largest scale, entire skyscrapers can be used for vertical farming, possibly including a restaurant or a supermarket where vegetables are sold. On a smaller scale, vegetables are harvested from the paths between the shelfs on which they grow. In this way, as Pinstrup-Andersen recently pointed out, indoor vertical farming may support improved nutrition, reduce water consumption and decrease the risks associated with outdoor farming due to increasing climate change and extreme weather conditions [4]. Particularly in highly urbanised areas, vertical farming may offer a certain amount of independence [5]. Interestingly, vertical farming can even compete economically with fresh food grown in greenhouses, despite the high cost of artificial lighting [6, 7]. From a technical point of view, relatively new technologies such as hydroponics, aeroponics and aquaponics facilitate efficient farming in the city [8–10]. Hydroponics is a hydroculture technology used to grow plants without soil, i.e. in water with additional nutrients, possibly using perlite or a similar structure, to support the roots of plants. Aeroponics goes one step further and grows plants in humid air or mist, but without inserting the roots in water. Finally, aquaponics uses another approach by creating a symbiosis between plants and aquatic animals, where water and animals' by-products are used as a source of nutrients for plants. It should be noted that the location and design of these technologies must be tailored carefully to achieve a sustainable food supply [11].

Another technology based on the same idea of growing plants vertically to save space is demonstrated by the BIQ Algenhaus in Hamburg, Germany. The façade of this building is used as a bioreactor in which microalgae are grown. During growth, the microalgae absorb the radiation on the façade, converting it partly into biomass, while the residual radiation is used for heating the building. Nutrients are provided by the waste water from the building, again achieving a high recycling rate that is seen in common vertical farming technologies [12].

Despite these advantages and even the possible necessity of vertical farming that could be only be mentioned briefly here, there is surprisingly little literature available about new technologies specifically for vertical farming. Even textile fabrics that are well-known as agrotextiles used to protect diverse plants from wind, low temperatures or insects cannot be found in literature about vertical farming. An overview will be given here of the possible use of different textile fabrics for vertical farming applications, subdivided into the farming of plants and algae.

2 Textile fabrics for algae immobilisation and harvesting

Algae are eukaryotes that are, depending on the cited study, regarded as simple plants or as plant-like species [13, 14]. A broad spectrum of algae exists, from the smallest micro-algae such as *Chlamydomonas reinhardtii*, a well-known model organism for photosynthesis or starch metabolism, to large seaweed formed by red, brown or green macro-algae. Several algae are studied comprehensively, as they can produce chlorophyll, carotenoids, fucoidans and other healthy ingredients. Other algae can be eaten, are used in cosmetics, can serve as a base for bio-ethanol, can be used to clean waste water, etc. Algae are thus of great interest in recent research, but are already farmed on a large scale, particularly in Asian countries such as China, Japan or Korea. Despite recent approaches to growing algae in a vertical arrangement, such as the BIQ Algenhaus [12], scientific literature mostly reports on common growth methods using bioreactors or round tanks.

Combinations with textile fabrics can only rarely be found in literature. Kerrison *et al.* describe textiles substrates for the macro-alga *Saccharina latissimi*, which was seeded on fabrics in different development stages. Using a binder solution, the seaweed-forming macro-alga was affixed to a polyester rope and a non-woven fabric. Facilitating the outplanting of algae in this way at a seaweed farm at an earlier stage not only increased the amount of biomass produced, but also helped decrease the necessary volume of hatchery tanks [15].

The seaweed *Gayralia sp.* was studied by Pellizzari *et al.* [16]. They found polypropylene nets placed close to a mangrove fringe in the bay in southern Brazil where they performed their experiment enabled cultivation using a simple technology and resulting in a reliable algae growth rate, and provided the local inhabitants a secure income.

An integrated photobioelectrochemical system, combining a microbial fuel cell with algae growth for domestic wastewater treatment, was suggested by Luo *et al.* [17]. In such a combination, electrogenic bacteria produce electricity through oxygen reduction, while at the same time degrading organic compounds. The algae produce oxygen by photosynthesis, thus eliminating the need for external aeration while also serving as biomass. Luo *et al.* studied six different mesh membranes from polyester or nylon with varying pore sizes, ranging from 0.11 mm to 5.31 mm for algal attachment to support algae harvesting, and found polyester slightly superior to nylon, while the smaller pore sizes of 0.11 mm and 0.53 mm resulted in significantly higher biomass productivity than the largest pore size.

Nylon meshes were also used by Lee *et al.* to increase the biomass productivity of diverse microalgae [18]. In addition, the harvesting and de-watering of the algal biomass were found to be easier and less expensive, as the meshes with adhered algae could simply be taken out of the culture.

Focusing on microalgae, electrospun nanofiber mats from polyamide and polyacrylonitrile were studied and compared with a non-woven polypropylene microfiber fabric (Figure 1) [19]. Cell adhesion, however, was poor, contrary to a previous study of *Chlamydomonas reinhardtii* on polysulfon nanofiber mats [20].

Gross *et al.* studied the effect of materials and structures on algal cell attachment. Working with a non-sterile *Chlorella vulgaris* culture including other diverse green algae and cyanobacteria, they investigated various metals, polymers and rubber. In addition to smooth surfaces, meshes with different pore sizes were studied. In general, polypropylene and nylon meshes with openings of 0.5–1.25 mm were found to be ideal for initial cell attachment and long-term adherent growth [21].

Different technologies were suggested for harvesting microalgae. Amongst them, filtration is a technology in which textile meshes or membranes are used. One possibility is the use of so-called microstrainers, rotating filters with fine meshes (pores measuring between 35 μm and 62 μm), combined with continuous backwash. Wilde *et al.* suggested a double-stage microstrainer to increase performance and cost-efficiency [22].

The exact mesh pore size for such filtration methods is determined by the size of the algae. *Chlorella sp.* (5–6 μm) and *Chlorella vulgaris* (0.1 μm) can be harvested through microfiltration [23, 24], while a microfiber disc filter was used for *Nannochloropsis salina* [25]. For *Chlorella pyrenoidosa*, Chu *et al.* studied a stainless steel mesh with a pore size of 75 μm, on which a diatomite cake layer was formed as the dynamic membrane module [26, 27]. For the dewatering of *Chlorella vulgaris*, Munshi *et al.* studied a forward osmosis polyethersulfone membrane, supported by a polypropylene permeable mesh to prevent membrane rupture, in combination with different draw solutions, such as NaCl or NH_4Cl,

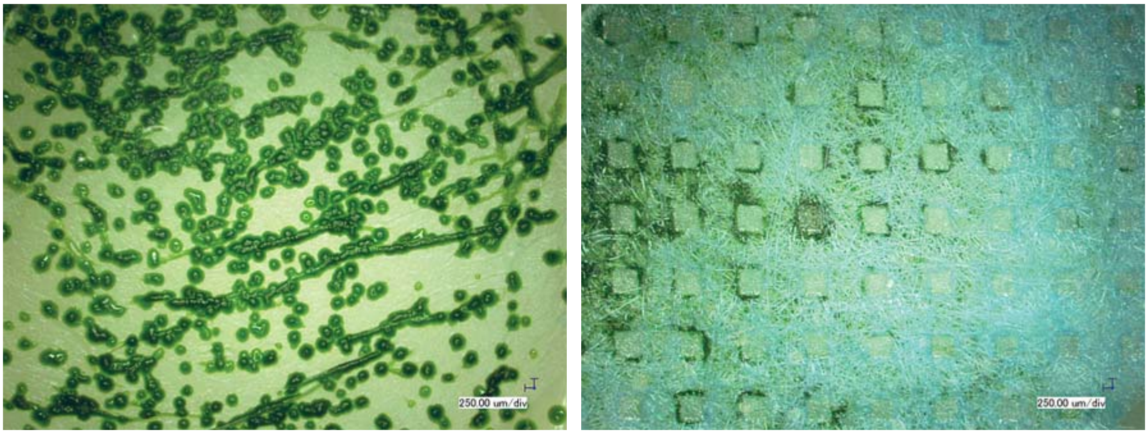

Figure 1: Growth of Chlamydomonas reinhardtii on a polyamide nanofiber mat (a) and on a polypropylene non-woven fabric (b). For a detailed description of the experiments, cf. Ref. 19.

and found this membrane combination generally suitable [28].

It should be mentioned that the opposite objective has been reported in several publications: textile fabrics can also be prepared to protect buildings from algae (particularly in consortia with bacteria) growing on them or to serve other biocidal functions [29].

While the possible uses of nets, membranes and several other textile structures for algae growth and harvesting described above exist, no research can be found in literature regarding woven, warp or weft knitted structures as substrates for algae growth.

Nevertheless, algae, particularly microalgae, belong to a species that can be of great interest for vertical farming, e.g. for vertical agriculture in space [30], while the outdoor cultivation of temperature-tolerant algae such as *Chlorella sorokiniana* in column photobioreactors may also be a research objective aimed at sustainable food production [31]. This suggests that there is a broad area of research of possible new findings and developments related to the growth of adherent algae on diverse textile fabrics with potential vertical farming applications.

3 Plants

Agrotextiles are typically used as covers, not as substrates for growing plants. Although they can be degraded by UV irradiation and the effects of weather, and then destroyed by mechanical impacts [32], their advantages seem to outweigh these problems.

In an unheated greenhouse during the winter, lettuce was found to grow best if covered by a combination of mulch and an agrotextile [33]. Outdoor studies showed that an agrotextile or polyethylene foil resulted in an increased lettuce yield in the early growth phase [34]. In another study, a cloth cover resulted in the strongest lettuce plants, while straw mulch resulted in the weakest plants [35]. Agrotextiles were found more suitable than black plastic and sawdust for strawberries with a high ascorbic acid content [36]. Traditional straw mulch, however, resulted in the best fruit size and yield [37]. For an early potato harvest, a covering made from agrotextiles resulted in larger potatoes than a covering made from a perforated plastic film or no covering at all [38]. On the other hand, litchi fruit harvesting periods could be delayed successfully by shading the trees with an agronet of 30% or 50% light transmission, thus preventing the ripening of all litchis within a few days [39].

Several research groups are working on different approaches to further develop these simple agrotextiles. Dan *et al.* developed a new textile composite material that was UV resistant and clearly increased the growth of spinach and two lettuce varieties [40]. A knitted alternative to typical non-woven fabrics was suggested by Scarlat *et al.*, who prepared warp knitted nets from polyester and polyamide, and found good mechanical properties compared with typical agrotextiles [41].

It should be mentioned that agrotextiles such as row covers are used to protect plants, not only from the wind and sun, but also from virus vectors and other undesirable pests. Honeydew melons could be protected from the sweet potato whitefly and vegetable leaf miner using different row covers with varying success [42]. For tomatoes, whiteflies are also a major pest that sometimes results in complete crop loss. In combination with planting aromatic basil between tomato rows, an agronet cover could reduce whitefly infestation by more than two thirds [43]. The same effect was found when French bean plants were protected from the silverleaf whitefly and black bean aphids. In addition, the covered plants developed faster and yielded a higher quality [44]. While the latter study showed no clear correlation between the protective effect and the impregnation of the net with an alphacypermethrin-based insecticide, another study found that the mortality rate of whiteflies exposed to alphacypermethrin-treated agronets doubled [45]. To prevent crops from bacterial contaminations, antibacterial nanosilver coatings were deposited on high-density polyethylene nets and studied with respect to their antibacterial properties on gram-positive and gram-negative bacteria [46].

To summarise these findings, textile fabrics can be used for a broad variety of agricultural applications, in particular protecting plants from excessively cold or warm weather, insects, bacterial contaminations, etc. It should be mentioned, however, that there are also some negative aspects that are usually not reported in literature, but must not be overlooked, such as birds and other animals becoming entangled in nets meant to protect fruit against them, or the exposure of the environment to non-biodegradable polymer parts if agrotextiles are destroyed by

a) b)

Figure 2: Growth of cress (a) and grass (b) in different textile substrates

heavy wind, etc. These aspects, however, are not relevant for indoor vertical farming, and can be addressed through intelligent textile constructions for outdoor vertical farming ideas.

Because the step from covering plants with agrotextiles to letting plants grow on agrotextiles in hydroponic applications is not actually large, it is surprising that no reports regarding other textile applications in agriculture can be found in scientific literature. Textile fabrics are commercially available as base materials for outdoor vertical farming systems for individuals, and contain bags in which plant pots can be fixed. However, the direct combination of textile and plant, i.e. using a fabric as a substrate to which the plant roots adhere, is only scarcely found. This is particularly hard to understand, as the shape and chemistry of textile fabrics can be tailored according to the requirements of the roots of each plant (Figure 2).

4 Conclusion and outlook

Textile fabrics are used for several applications in agriculture and algae farming. Surprisingly, no reports can be found in scientific literature about the obvious implications of studying the ability of diverse textile fabrics for their possible use in hydroponics and other vertical farming applications.

Due to the increasing need for vertical farming solutions in the coming decades, vertical farming can be developed further based on the well-known advantages of textile fabrics: the wide variety of structures and chemical compositions of fibres, the possibilities of creating one-, two- and, to a certain extent, even three-dimensional fabrics, and relatively inexpensive and long-established textile production technologies.

In the author's personal opinion, vertical farming is a technologically available method to address the severe problem of supplying sufficient food for a growing population in cities with increasingly less space, without destroying even more forests and other natural wildlife habitats. Numerous examples of the use of textile fabrics for diverse agricultural applications suggest that recent progress in innovative agrotextiles and algae harvesting nets should be transferred into textile-based solutions for vertical farming. This transfer could pave the way to new technologies for ecologically and economically reasonable food production.

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