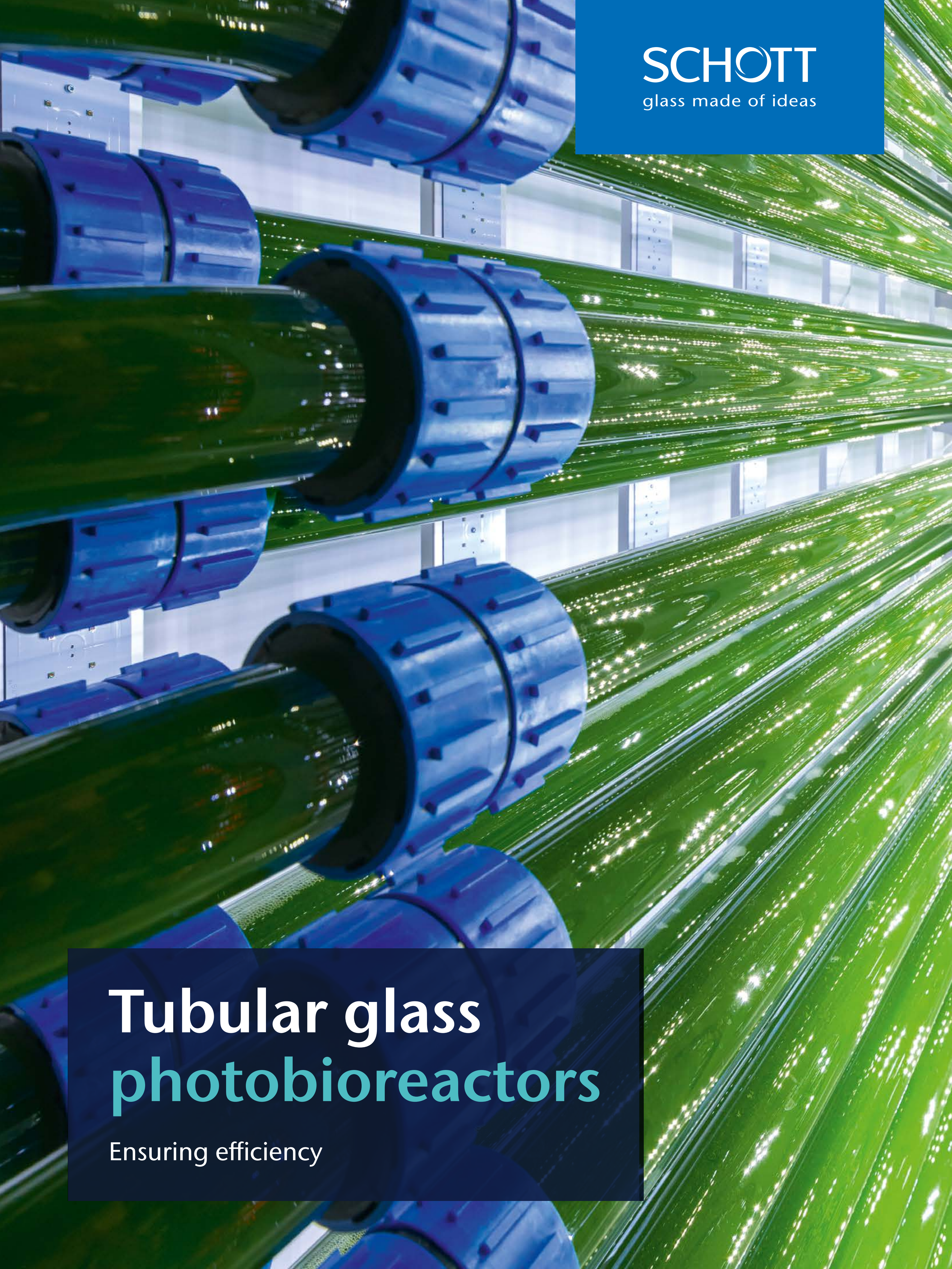
SCHOTT
glass made of ideas



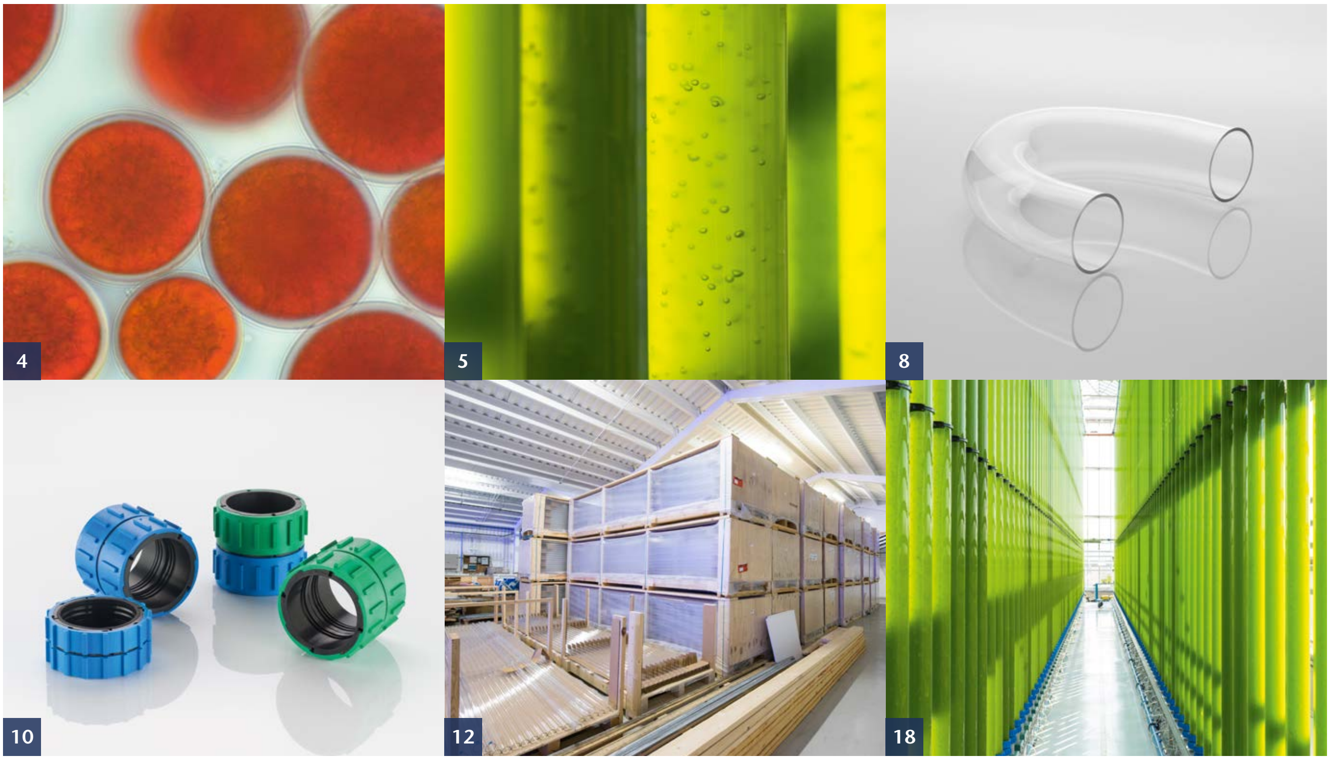
Tubular glass photobioreactors

Ensuring efficiency

Where others say no, we say yes. Because at SCHOTT we believe that shared responsibility can release the energy to achieve the impossible. As a global material technology group, we are constantly exploring unique and innovative ways to make a difference for businesses and people. Being a foundation company, SCHOTT has anchored responsibility, scientific research, society and the environment deeply in its DNA. Represented in over 30 countries by 17,100 employees, we are a highly skilled partner for many high-tech industries. Whatever challenges the future might hold, we can't wait to come up with innovative solutions and turn visions into reality.

With a production capacity of round about 230,000 tons and production sites in Europe, South America and Asia, SCHOTT Tubing is one of the world's leading manufacturers of glass tubes, rods and profiles. More than 60 different glass types are produced in a large variety of dimensional and cosmetic specifications based on a standardized production process and a global quality assurance system. SCHOTT Tubing provides customized products and services for international growth markets such as pharmaceuticals and electronics as well as industrial and environmental engineering.

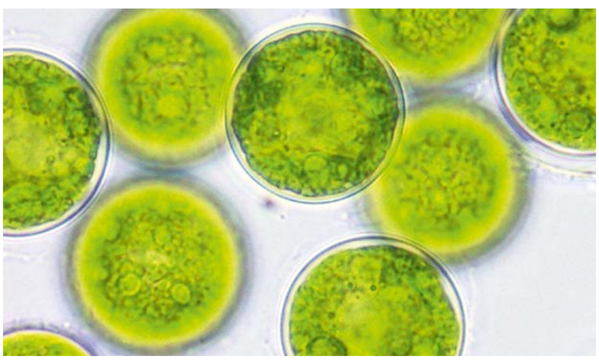
Title



Contents

Algae production systems

Common photosynthetic algae cultivation systems are either open ponds or closed photobioreactors (PBRs).



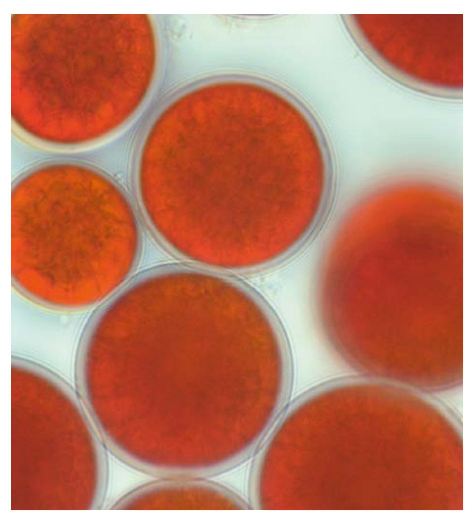
Open ponds

Open ponds are typically built in circular or raceway configurations. The water is kept in motion, for example by paddle wheels. Open ponds are seemingly inexpensive and easy to build. However, poor light utilization, danger of contamination and high water evaporation are the main challenges, which lead to low biomass output per area and large water uptake. Some difficulties can be overcome by rooftops however this increases the costs further.

Closed system

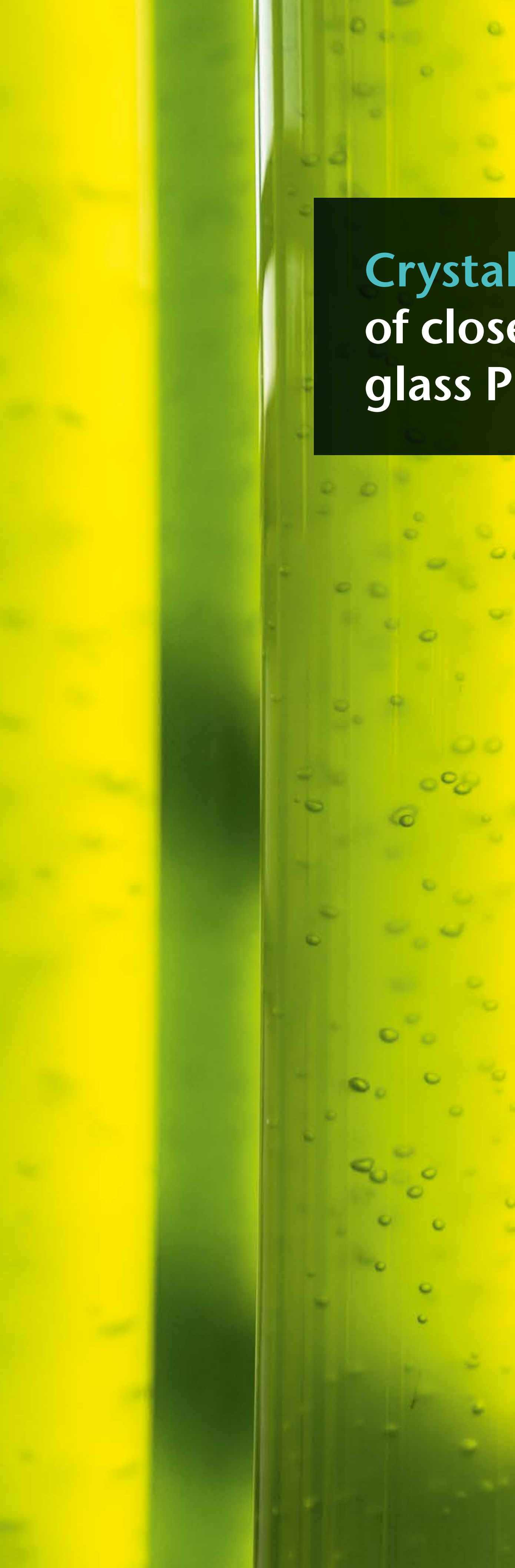
Closed systems are dominated by tubular and flat-plate reactors. Other options are bags, coils or domes. Flat plate systems have received a lot of attention due to their large illuminated surface area, but the technology suffers from heating problems and a strong tendency to build up biofilm formations on the inner walls. Tubular systems on the other hand reduce these drawbacks while maintaining the advantages of optimal light input and high productivity.

Therefore closed tubular glass Photobioreactors (PBRs) with long lifetimes and easy cleanability, are very well suited for the highly reproducible cultivation of algae resulting in the highest possible growth rates. As such, tubular glass PBRs are best suited to provide biosecurity for high quality inoculum used in open ponds.



Upper photo
Haematococcus pluvialis, green phase
Lower photo
Haematococcus pluvialis, red phase

Right
Closed vertical tubular glass PBR system



Crystal clear benefits of closed tubular glass PBR systems

Biosecure
protection against bio-contamination and culture crashes

Productive
80 – 160 l/m² photoactive volume, PBR height up to 6 m

Cost efficient
little maintenance and low total cost of ownership

Durable
sustainable light transmission T > 95 % (air – glass – water), lifetime of 50 years and more

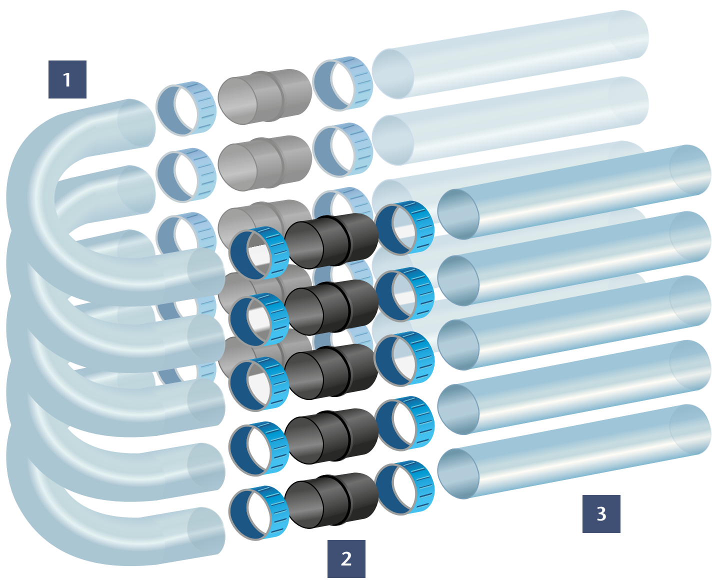
Resistant
against chemicals, corrosion, sagging, scratches, UV-light

Food safe
food and pharma grade

Product range

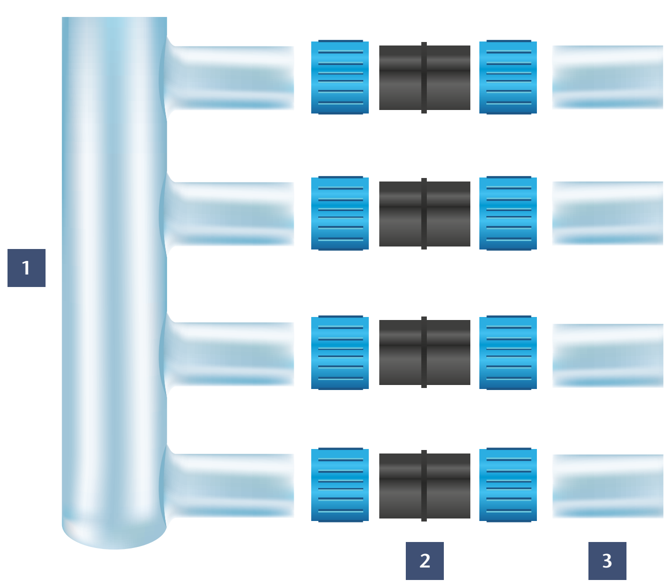
Overview

Helical system



1 U-bend
2 Coupling
3 Tubing

Fence system



horizontal
or vertical
orientation

1 Manifold
2 Coupling
3 Tubing

Product range

Borosilicate glass tubing

Item no.	Joint outside diameter mm in	Joint wall thickness mm in	Tube length m ft	Volume per tube l gal	Package type*	Package content Number of tubes	Weight approx. kg approx. lb
1535285	54 ± 0.65 2.13 ± 0.03	1.8 ± 0.18 0.07 ± 0.01	1.4 4.6	2.79 0.74	carton	9	8.3 18.3
					pallet	180	166 366
1522883			2.5 8.2	4.99 1.32	carton	12	19.7 43.5
					pallet	144	236.4 522
1523124			5.5 18	10.97 2.90	wooden box	56	202.6 430.8
1534297					pallet	238	861.2 1898.6
1500383	65 ± 0.65 2.56 ± 0.03	2.2 ± 0.18 0.09 ± 0.01	1.4 4.6	4.04 1.07	carton	9	12.2 26.9
					pallet	180	244 538
1511901			2.5 8.2	7.21 1.90	carton	9	21.8 48.0
					pallet	108	261.6 576
1459938			5.5 18	15.86 4.19	wooden box	36	191.6 422.3
1534302					pallet	165	877.9 1935.5

*for explanation regarding package type please see page 12
Other dimensions upon request.
Glass tubing for algae cultivation must be stored in dry conditions in closed buildings. For storing pallets and wooden boxes with glass tubing, the floor must be level and horizontal and have a load-bearing capacity of 1,000 kg/m². Do not stack more than 3 pallets on top of each other.

Borosilicate glass U-bends

Helical system

Item no.	Joint outside diameter (mm / in)	Joint wall thickness (mm / in)	Joint U-bend width (mm / in)	Approx. U-bend height (mm / in)	Straight side length (mm / in)	Volume per bend (approx.) (l / gal)	Package type	Package content (Number of tubes)
1534644	54 ± 0.65 2.13 ± 0.02	2.5 ± 0.20 0.10 ± 0.01	234 ± 2.00 9.21 ± 0.08	200 7.87	> 45 > 1.77	0.85 0.22	carton	33
							pallet	396
1436672	65 ± 0.65 2.56 ± 0.03	2.8 ± 0.20 0.11 ± 0.01	245 ± 2.00 9.65 ± 0.08	200 7.87	> 45 > 1.77	1.2 0.32	carton	21
							pallet	252

Glass U-bends for algae cultivation must be stored in dry conditions in closed buildings.

Product range

Borosilicate glass manifolds

Fence system

Manifolds and couplings, fence system © Jongerius ecoduna GmbH

Manifolds are placed at the tops or at the ends of tubular PBR fences and function as U-bends and in- and outlets.

- Biosecure and food safe, full glass solution
- Available with closed ends or with flange
- Outside diameter of arms: 54 mm or 65 mm for use with standard couplings
- Number of arms, distance between arms, total length etc. are customized with a minimum order quantity of 25 pieces

Description*	Package	Package content	Minimum Order Quantity (MOQ)
Manifolds 10 arms closed 54 mm			25
Manifolds 5 arms flange 54 mm			25
Manifolds 8 arms closed 65 mm			25
Manifolds 4 arms flange 65 mm			25
Manifolds 6 arms open 65 mm	carton	2	1 pallet
	pallet	36	

*closed: both ends closed/flange: one side closed, one side flange/open: both sides flange
Glass manifolds for algae cultivation must be stored in dry conditions in closed buildings.

Product range

Couplings

SCHOTT tool kit

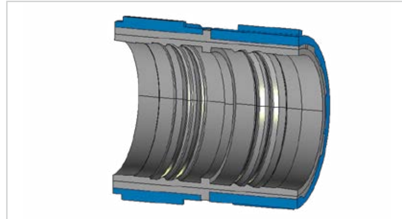
Open standard coupling

Open standard slim coupling

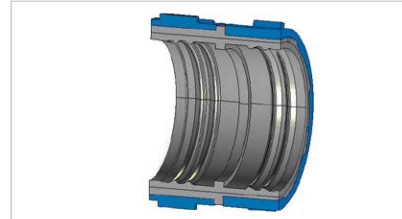
*see page 17

Specially developed for tubular photobioreactors:
The couplings are designed for SCHOTT glass tubes with plain tube ends according to the product range shown in this brochure.

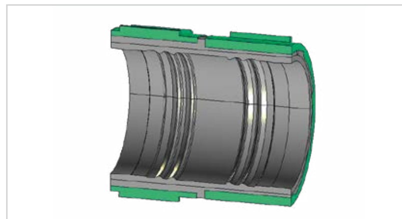
- Successfully tested for 10 years lifetime* regarding
  - 3 bar pressure resistance
  - UV-resistance
  - Regular cleaning cycles with various chemicals
- Fast installation allowing for reduced built up time of the reactor
- Easy to disassemble and re-use allowing for fast modification or extension of a reactor system
- Easy handling with pre-assembled devices and a special tool kit including a torque wrench (**Standard couplings: 40 Nm**, Slim **couplings 25 Nm**)
- Food grade



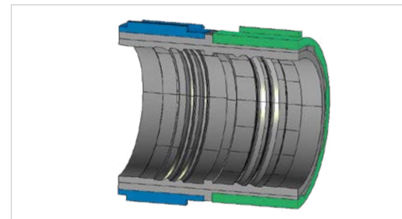
1 Standard, length 80 mm
Partition wall to assure glass separation and smooth transition (torque wrench 40 Nm needed)



2 Standard Slim, length 45 mm
(torque wrench 25 Nm needed)



3 Maintenance, length 80 mm
Allows easy exchange of tubes, no partition wall



4 Adapter, length 80 mm
Allows connection to pheriphery tubes with 2.5 in outer diameter

Item no.	Outside diameter tube mm | in	Package Number of couplings		Description	Package Weight approx. kg | approx. lb
1530116	54 | 2.13	24	bag	Standard [1]	6.9 | 15.3
		960	pallet		277.7 | 612.2
1581056		24	bag	Standard Slim [2]	3.0 | 7.0
		1824	pallet		226.2 | 530.8
1463260	65 | 2.56	24	bag	Standard [1]	6.1 | 13.4
		960	pallet		219.4 | 483.7
1581035		24	bag	Standard Slim [2]	3.2 | 6.6
		1824	pallet		240.8 | 498.6

Toolbox 54
Standard with torque wrench **40 Nm** for closing of coupling and tools for opening

Toolbox 54
Slim with torque wrench 25 Nm for closing of coupling and tools for opening

Toolbox 65
Standard with torque wrench **40 Nm** for closing of coupling and tools for opening

Toolbox 65
Slim with torque wrench **25 Nm** for closing of coupling and tools for opening

Additional equipment

Item no.	Outside diameter tube mm | in	Package Number of couplings		Description	Package Weight approx. kg | approx. lb
1530120	54 | 2.13	4	carton	Maintenance kit (no partition wall) [3]	0.9 | 2.0
		576	pallet		
1530105	65 | 2.56	4	carton	Maintenance kit (no partition wall) [3]	1.0 | 2.2
		576	pallet		
1534828	65 | 2.56	4	carton	Adapter [4]	1.0 | 2.2
		576	pallet		

Couplings for algae cultivation must be stored in dry conditions in closed buildings.

Packaging

Bags

- Couplings

Cartons

- Tubes, up to 2.5 m length
- U-bends
- Couplings
- Manifolds

Wooden boxes and special pallets

- Tubes, 5.5 m length
- smaller quantities

All products from SCHOTT for algae cultivation must be stored in dry conditions in closed buildings. For storing pallets and wooden boxes with glass tubing, the floor must be level and horizontal and have a load-bearing capacity of 1,000 kg/m^2. Do not stack more than 3 pallets on top of each other.

Borosilicate glass properties

DURAN®

	Metric	US
Coefficient of mean linear thermal expansion α acc. to DIN ISO 7991	$3.3 \cdot 10^{-6}$ K^{-1} (20 °C; 300 °C)	$3.3 \cdot 10^{-6}$ K^{-1} (68 °F; 572 °F)
Transformation temperature T_g	525 °C	977 °F
Density ρ at 25 °C	2.23 g $\cdot$ cm^{-3}	139.2 lb $\cdot$ ft^{-3}
Modulus of elasticity E (Young's modulus)	$63 \cdot 10^3$ N $\cdot$ mm^{-2}	$91 \cdot 10^5$ lb $\cdot$ in^{-2} (psi)
Poisson's ratio μ	0.20	0.20
Thermal conductivity λ_w at 90 °C	1.2 W $\cdot$ m^{-1} $\cdot$ K^{-1}	0.69 Btu $\cdot$ hr^{-1} $\cdot$ ft^{-1} $\cdot$ °F^{-1}
Refractive index (λ = 587.6 nm) n_d	1.473	1.473
Stress-optical coefficient (DIN 52 314) K	$4.0 \cdot 10^{-6}$ mm^2 $\cdot$ N^{-1}	$4.0 \cdot 10^{-6}$ mm^2 $\cdot$ N^{-1}

Chemical composition			
SiO_2	B_2O_3	Na_2O + K_2O	Al_2O_3
81	13	4	2

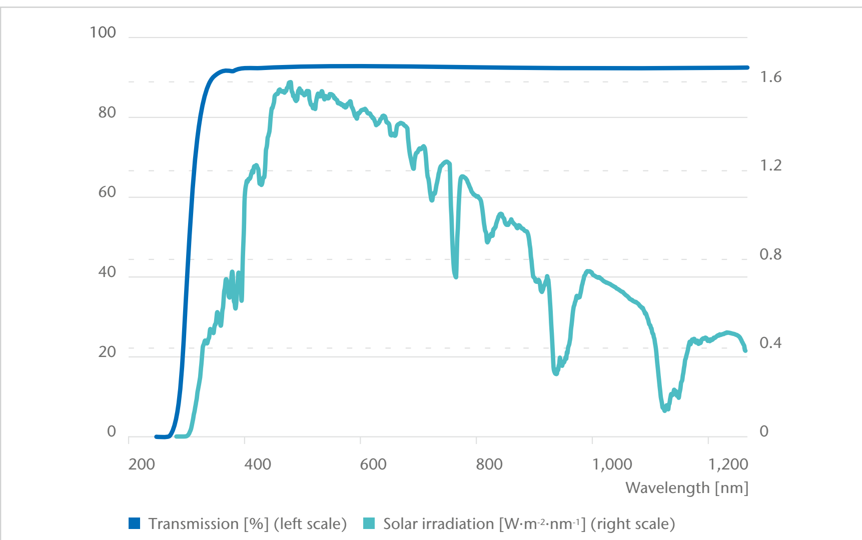
main components in approx. weight %

Chemical resistance	
Hydrolytic Class (DIN ISO 719)	HGB 1
Acid Class (DIN 12116)	Class S 1
Alkali Class (DIN ISO 695)	Class A 2

Borosilicate glass properties

DURAN®

Transmission



Transmission of DURAN® glass (d = 2.2mm) in configuration air/glass/air.

Note
When the glass tube is filled with water, the transmission increases from about 92 % to 95.6 % due to reduced reflection losses at the inner glass/water interface.

Pressure resistance of tubing made of borosilicate glass

The following formulas apply to stress free, pristine tubing and cylindrical hollow bodies with a circular profile, uniform wall thickness with open ends, free from thermal load, under internal positive pressure.

Estimation of the maximum pressure resistance (p)

$$p = \frac{WT \cdot 140\ \text{bar}}{OD - WT}$$

Estimation of the minimum wall thickness (WT)

$$WT = \frac{OD \cdot p}{140\ \text{bar} + p}$$

$$\frac{K}{S} = 70\ \text{bar}$$

Permissible load referring to standard DIN EN 1595: “Pressure equipment made from borosilicate glass 3.3 – general rules for design, manufacture and testing”

OD = Outside Diameter in [mm]
WT = Wall Thickness in [mm]
p = Pressure Resistance in [bar]

Other points to be considered:
- AD 2000-leaflet N 4, edition 2000-10: Pressure vessels made of glass, with encl. 1, edition 2000-10: evaluation of faults in walls of glass pressure containers
- AD 2000-leaflet B 1, edition 2000-10: cylindrical and spherical shells under internal pressure overload

According to DIN EN 1595: “Pressure equipment made from borosilicate glass 3.3 – general rules for design, manufacture and testing”, DURAN® approved material and may be used for the construction of pressure equipment.

Pressure drop in tubular photobioreactors

Pressure loss

In general, the pressure drop can be calculated for any velocity using the following formula.

$$\Delta p = \zeta \cdot \frac{\rho}{2} \cdot u^2$$

Δp: pressure loss
ζ: pressure loss number (zeta)
ρ: algae culture density
u: linear velocity of algae culture

u = 0.7 m/s	ζ	Δp [Pa]
Round tube (D = 65 mm, WT = 2.2 mm, L = 5.5 m)	1.96	480
U-bend (D = 65 mm, WT = 2.8 mm)	0.252	62

Pressure drop of a tube and a U-bend at the given velocity, *u*. D is the outer diameter, WT the wall thickness. The algae culture's density was approximated with $\rho = 1$ g/cm³.

Electrical power

The electrical power of the pumps, P_{el}, scales with the pressure drop and the volume flow, Q:

$$P_{el} = \frac{\Delta p \cdot Q}{\eta_p}$$

P_{el}: electrical power
Δp: sum of pressure loss in Pa
Q: volume flow rate in m^3/s
η_p: pump efficiency at operating point ($0 < \eta_p < 1$)

Research done in cooperation with: Institute of Fluid Dynamics, LSTM, Technical Faculty, University Erlangen-Nuremberg, Germany

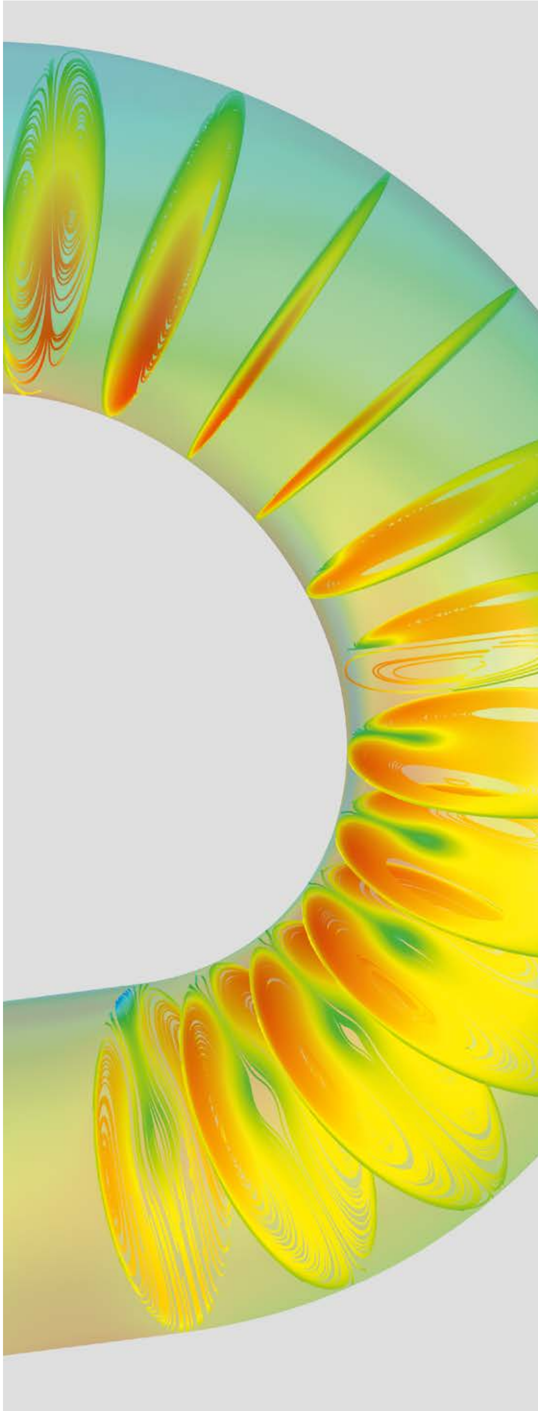


Figure: Dean-vortex appearance in an U-bend – computer simulation (ANSYS® CFX® 14.5.7)

Features and benefits

Closed tubular photobioreactors versus open ponds

Closed tubular photobioreactor

Open pond

Contamination
- Very low risk of contamination compared to open ponds, where other microorganisms or insects have easy access
- No limitation regarding the algae species that can be grown, also due to effective blocking against competing organisms

Productivity
- Higher productivity in terms of mass per area and day
- Significantly higher volumetric productivity

Algae concentration at harvest
- Notably higher concentration in terms of mass per liter
- More efficient harvesting procedure

Water loss
- No evaporation within closed system compared to open ponds, which can lose significant water amounts, resulting in salinization
- Water loss is limited to external factors, such as the cooling process

Biomass quality
- Biomass quality is highly reproducible due to excellent process control of tubular PBR systems
- High value products or high quality inoculum can be produced with optimum reliability

Production flexibility
- Easy cleanability allowing for defined initial status any time, thus switching algae species is possible and secure

Use of GMO* for improved production process
- GMO production is possible with closed reactor design

*GMO = Genetically Modified Organism

Borosilicate glass versus polymer materials

Light transmission

- Excellent light transmission (see page 14 for details)
- No solarization or browning effect
- No UV-protective additive or coating necessary to secure material properties

Fire protection

- Glass does not burn or give off toxic fumes

Leaching

- Glass is a chemically highly resistant material. With plastic tubing, depending on the polymer type, monomers or oligomers of hazardous substances such as Bisphenolmolecules can be leached into the algae culture.

Cleaning

- Mechanical stability allows continous in-line cleaning with polymer pellets
- Chemical stability allows cleaning in place (CIP)
- Lower material and maintenance costs compared to quality polymer tubes

Thermal stability

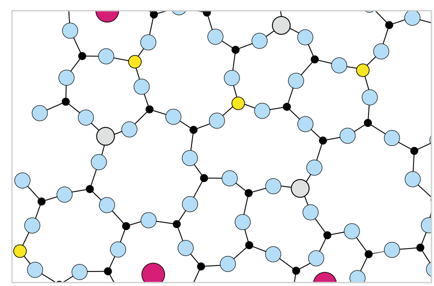
- No need for expansion loops due to low thermal expansion; Example: For 5.5 m long tubes and a temperature increase of 20 °C/36 °F the expansion of Borosilicate glass is only 0.36 mm/0.01'' while polymers expand from 3.3–8.8 mm/0.13''–0.35'' depending on polymer type.

Cost saving

- Glass components can last fifty years and longer
- Reduced number of rack poles. High mechanical stability allows increased support distances without significant sagging of tubes (see picture on right)

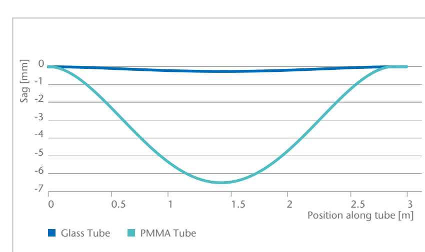
Sagging

- No permanent deformation of glass tubes in contrast to polymer tubes



Borosilicate glass

Polymer



Sagging of water filled tubes
(outer diameter 65 mm, wall thickness 2.2 mm, length 2.75 m).
The sag of the glass and polymer tubes is 0.5 mm and 6.6 mm, respectively. The polymer tube would need to be supported every 1.5 m for the same sag as the glass tube.

References

of glass tubular photobioreactors

SCHOTT has formed alliances and partnerships all over the world. This allows us to provide complete tubular photobioreactors according to your needs. Please contact us for further details.

1 © Algalíf Iceland ehf., Iceland
2 © Varicon Aqua Solutions Ltd., UK, Phyco-Flow PBR at OP Bio, Japan
3 © A4F-Algae for Future, Portugal
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5 © Lgem AlgaeHUB®, Netherlands
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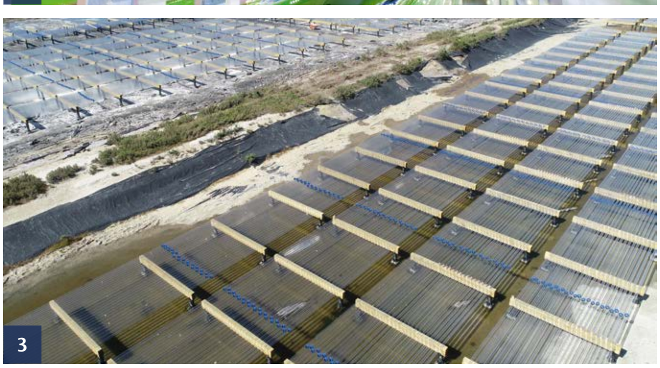
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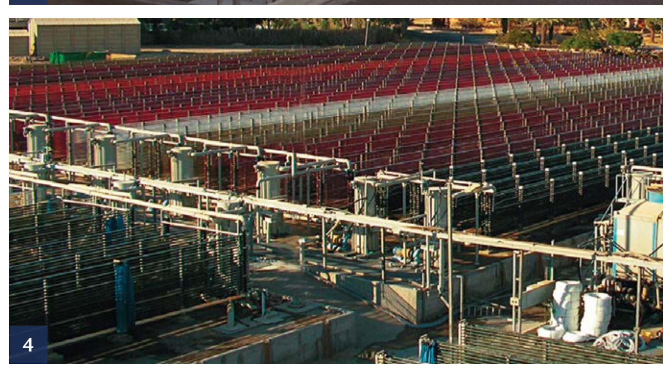
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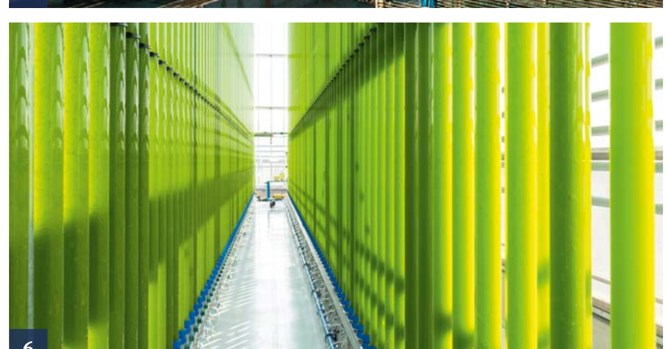
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Technical performance specification

Detailed information on permissible faults, definition of faults, testing methods and testing units are available upon request. Reduced tolerances are also available upon request. Regarding quality issues the relevant "Technical performance specification" (TPS) for the application apply to all sales and are binding unless separate written agreements with respect to specification have been agreed upon.

We thank our customers and partners for their kind assistence in providing product samples and photos.

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