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BIOINDICATION WITH PROTISTS IN THE ACTIVATED SLUDGE PROCESS: SOLUTION OF THE TAXONOMIC IMPEDIMENT

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Summary

Historically, one might recognize three principal periods in using protists as indicators in the activated sludge process. The Age of Discovery and Exploitation may be set between 1914 and 1950 when Ardern & Lockett (1914) created the term "activated sludge" and several scientists recognized the importance of protists in the cleaning process. The Age of Bloom may be set between 1950 and 2000. It commenced with the revision of the saprobic system (Liebmann 1951, 1958) and the studies of Curds & Cockburn (1970a, b). Now the field developed rapidly because several protistological groups dealt with activated sludge and practical indices were developed classifying the performance of sewage plants (Madoni 1994). Since the turn of the century, we are in a Period of Decline mainly because most of the young biologists don´t like identification and taxonomy of microscopic organisms although very useful identification literature is available (Berger & Foissner 2003) and shown in my lecture and in a practical demonstration. Further, I provide a Table showing what is indicated by certain organism species and communities.

Introduction

Historically, one might recognize three principal periods in using protists as indicators in waste water purification. The periods are connected with technical innovations in the water works and the increasing concern of the society about the heavy pollution of many rivers and lakes by organic and inorganic wastes in the industrialized countries.

The Age of Discovery and Exploitation may be set between 1914 and 1950 when Ardern & Lockett (1914) created the term "activated sludge" and researchers recognized the importance of protists in cleaning the waste water during the activated sludge process (Barker 1942, 1943, Liebmann 1936).

The Age of Bloom may be set between 1950 and 2000. It started with the revision of the saprobic system by Liebmann (1951, 1958), who recognized the usefulness of protists as indicators of water pollution when combined with metazoans and some physico-chemical parameters. These and other data were used by Curds (1966) and Curds & Cockburn (1970a, b) to update bioindication in waste water treatments plants. Their faunistic and experimental studies lay the ground for a scientific treatment of the field. They showed which ciliate species dominate in sewage plants and demonstrated their significance for a clear effluent (Fig. 1).

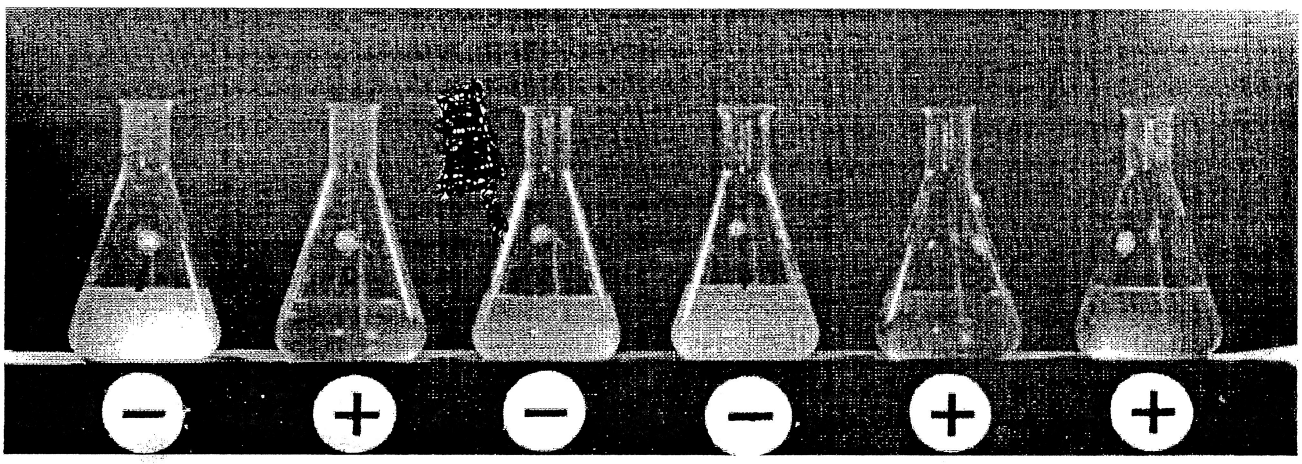


Fig. 6.3. Photograph of effluents issuing from laboratory-scale pilot plants operating in the presence (+) and absence (–) of ciliated protozoa (from Curds 1992)

The increasing concern of the society on river and lake pollution caused stronger government regulations and thus a massive increase in the number of sewage-treatment works. Concomitantly, problems with the performance of sewage plants increased, such as sludge bulking and poor effluent contaminating the rivers. This stimulated much protistological research on activated sludge, viz., by Curds in England, Fernández-Galiano in Spain, Bick in Germany, Madoni in Italy, Jenkins in the U.S.A., and my group in Austria. Soon, the number of students and postdocs increased and hundreds of faunistic, ecological, and taxonomical papers were published and finally collected in excellent reviews: Berger & Foissner (2003), Buck & Buck (1980), Curds (1982, 1992), Eikelboom & van Buijsen (1992), Foissner & Berger (1996), Foissner *et al.* (1991, 1992, 1994, 1995, 1999), Ganner *et al.* (2002), Jenkins *et al.* (2004), Kinner (1984), Madoni (1991, 1994), Mudrak & Kunst (1994), Pauli *et al.* (2001), Schleypen & Gschlössl (1992), Scherb (1968), and Sládeček (1973).

During this period practical tools were developed, i. e., methods and indices classifying the performance of sewage plants (Al-Shahwani & Horan 1991, Curds & Cockburn 1970b, Madoni 1994, Schleypen & Gschlössl 1992) and specific identification keys were published (Berger & Foissner, 2003, Berger *et al.*, 1997, Fernández-Galiano *et al.* 1996, Foissner & Berger 1996, Foissner *et al.* 1991, 1992, 1994, 1995, 1999). Thus, all was prepared for a successful development of the field. But things turned out differently.

The Age of Decline commenced around the turn of the century and continues. It is characterized by a distinct decrease in the number of scientific papers and loss of taxonomic knowledge, partially due to a massive change in the society but also due to a saturation of the field. Presently, most students and young scientists are unwilling to identify microscopic organisms and to do taxonomic work – in spite of the good identification literature and unemployment – because it has low social reputation and of only vague interest in the matter. Indeed, I observed several times that colleagues who became employed in river pollution classification soon stopped identification work and allocated it to technical assistants!.

Thus, my lecture has two goals: first, to show how simple it is for an academic biologist to identify the few organisms occurring frequently in activated sludge and second to provide a Table showing what is indicated by certain organismic communities and species.

Release from the taxonomic impediment

Whatever you want identify, plants, microscopic organisms, or beer mats, it needs good basic knowledge and some enthusiasm, as any work. The protists are a bit uncomfortable because they are so small that a microscope is needed. However, when you agree that a sewage biologist should be an academic then the person should be able to overcome this peculiarity, even in the time of molecular biology where classic morphology is usually strongly neglected in the university education. Of course, you need a good identification key, i. e., flow charts where the organisms are shown.

The electronic key you get is the most recent one and guides to 357 common ciliate species, of course including those frequently occurring in activated sludge. The guide, which is in English language and has 160 pages solves not only the taxonomic impediment but informs you on many other things, such as biomass and indicator value of the individual species as well as on ciliate morphology and terminology (Berger & Foissner 2003). This I shall show you now on 17 slides using peritrichs as an example because there are many misidentifications in the literature.

Possibly, I should mention that a reliable method for molecular identification of sewage ciliate species is not available but the first trial is promising (Marsh *et al.* 1998).

Sewage plant performance by bioindication

Although the compilation in Table 1 is far from being complete, it shows that sewage plant performance by bioindication is possible to a certain extent but it is not the philosopher´s stone. It is a valuable, integrative method that gives information on plant performance some weeks before and after the investigation. I think progress is possible, especially when the identification of the organisms is improved and a combined view is applied, i. e., when the plant type, the structure of the flocs, the bacterial community, and the usual physico-chemical parameters are taken into account.

Fig. 1 Illustrated guide and ecological notes to ciliate indicator species (Protozoa, Ciliophora) in running waters, lakes, and sewage plants

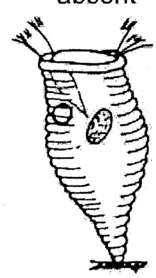
H. BERGER AND W. FOISSNER

Peritrichia I[1]

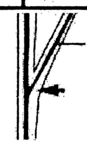
Volume II

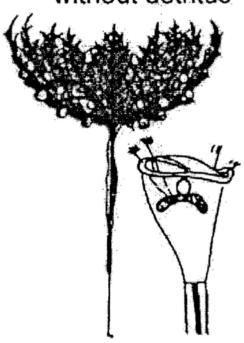
lorica

- present → **Peritrichia IV**
- absent[2] → **mode of life**[3]
  - epizoic → **Peritrichia VI**
  - mobile → **Peritrichia V**
  - sessile, usually not epizoic → **stalk; stalk diameter**
    - absent
    - not ramified; usually < 10 µm[4] → **Peritrichia II**
    - ramified; usually > 10 µm → **stalk muscle**
      - absent → **Peritrichia III**
      - present → **stalk muscle at ramification**
        - interrupted (arrow)
        - connected (arrow) *Zoothamnium* → **ramification of stalk; pellicle**
          - umbel-like; without detritus
          - dichotom; without detritus
          - dichotom; with detritus

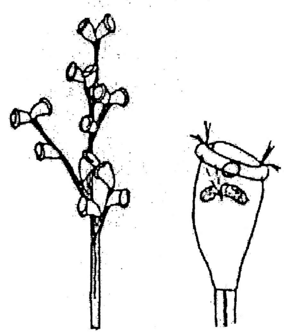


Scyphidia rugosa
about 90 µm (p.249)

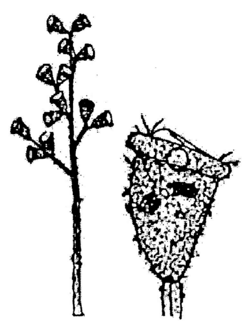




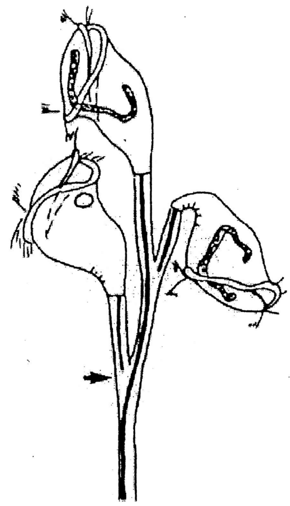
Z. arbuscula
40-70 µm (p.152)



Z. procerius
60-80 µm (p.163)



Z. kentii
50-90 µm (p.158)



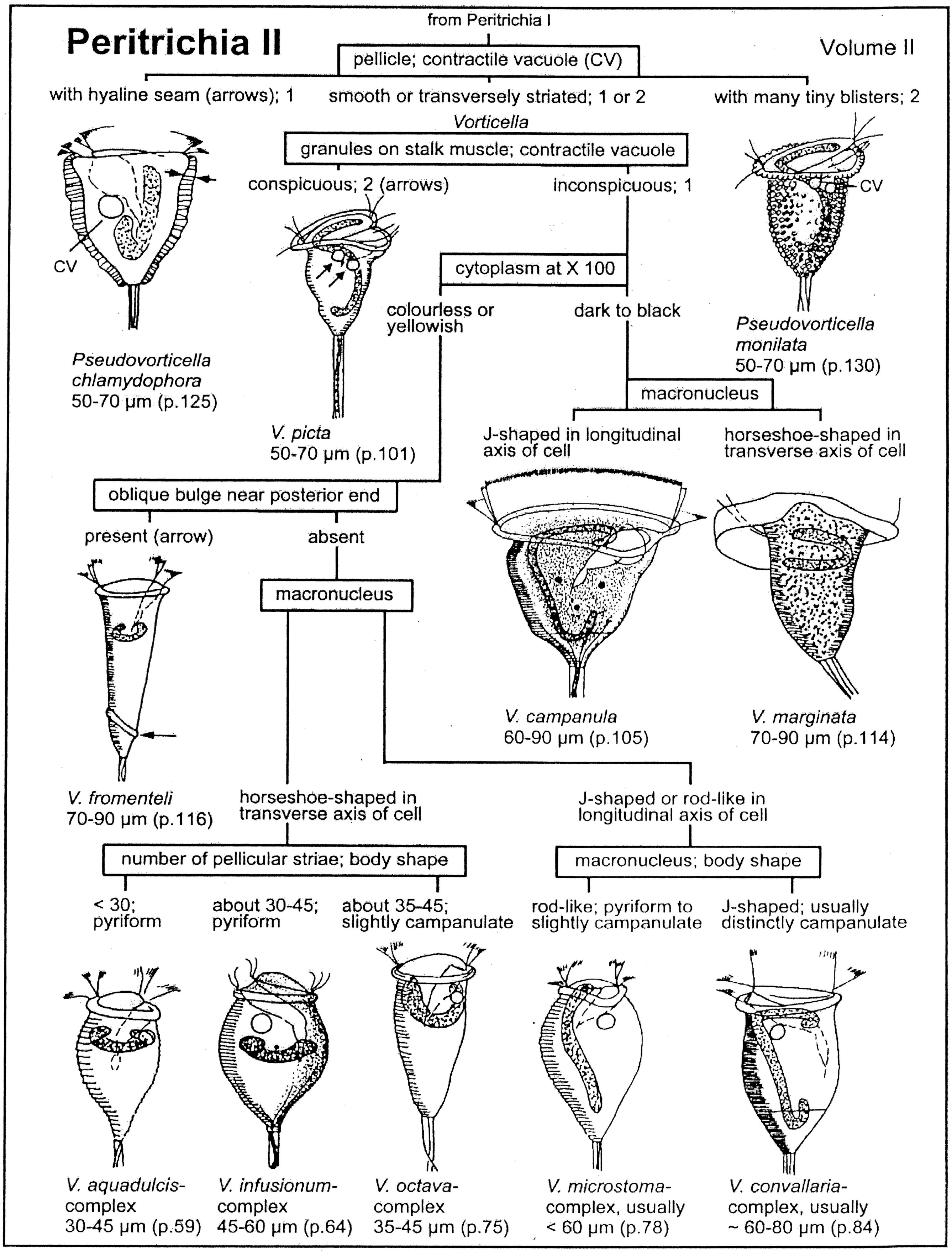
Carchesium polypinum
80-140 µm (p.137)

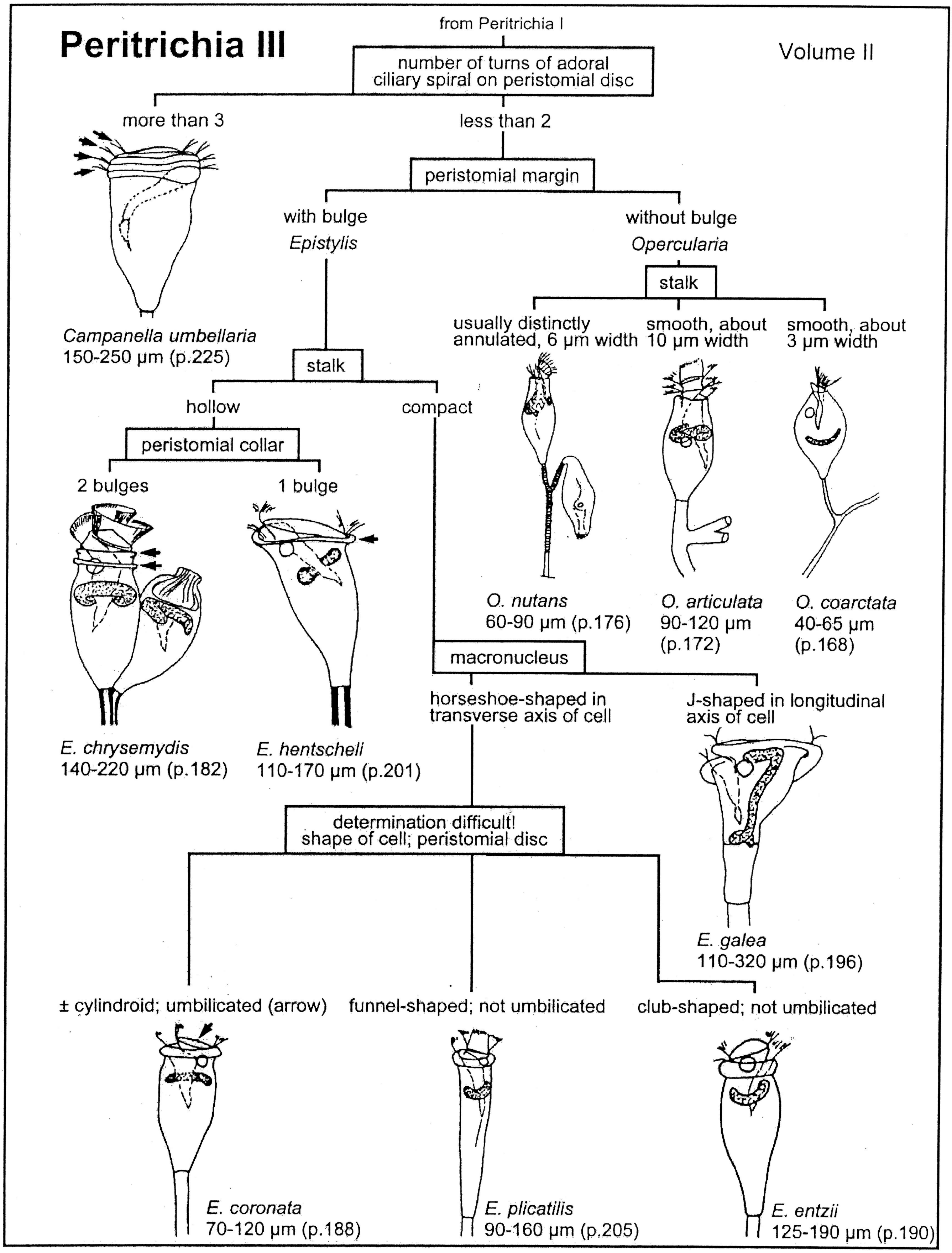
[1] The determination of most peritrich ciliates is simple because they have many distinct characters which, however, are often recognizable only in vital populations. Thus, samples must be investigated within few hours because most species soon become morbid in the collection jars or transform to swarmers which are indeterminable. This should be considered when samples are collected: many peritrichs form whitish lawns on macrophytes, mosses, and the underside of stones. Such lawns should be picked up with a pipette and collected in a separate vessel, which greatly facilitates determination.

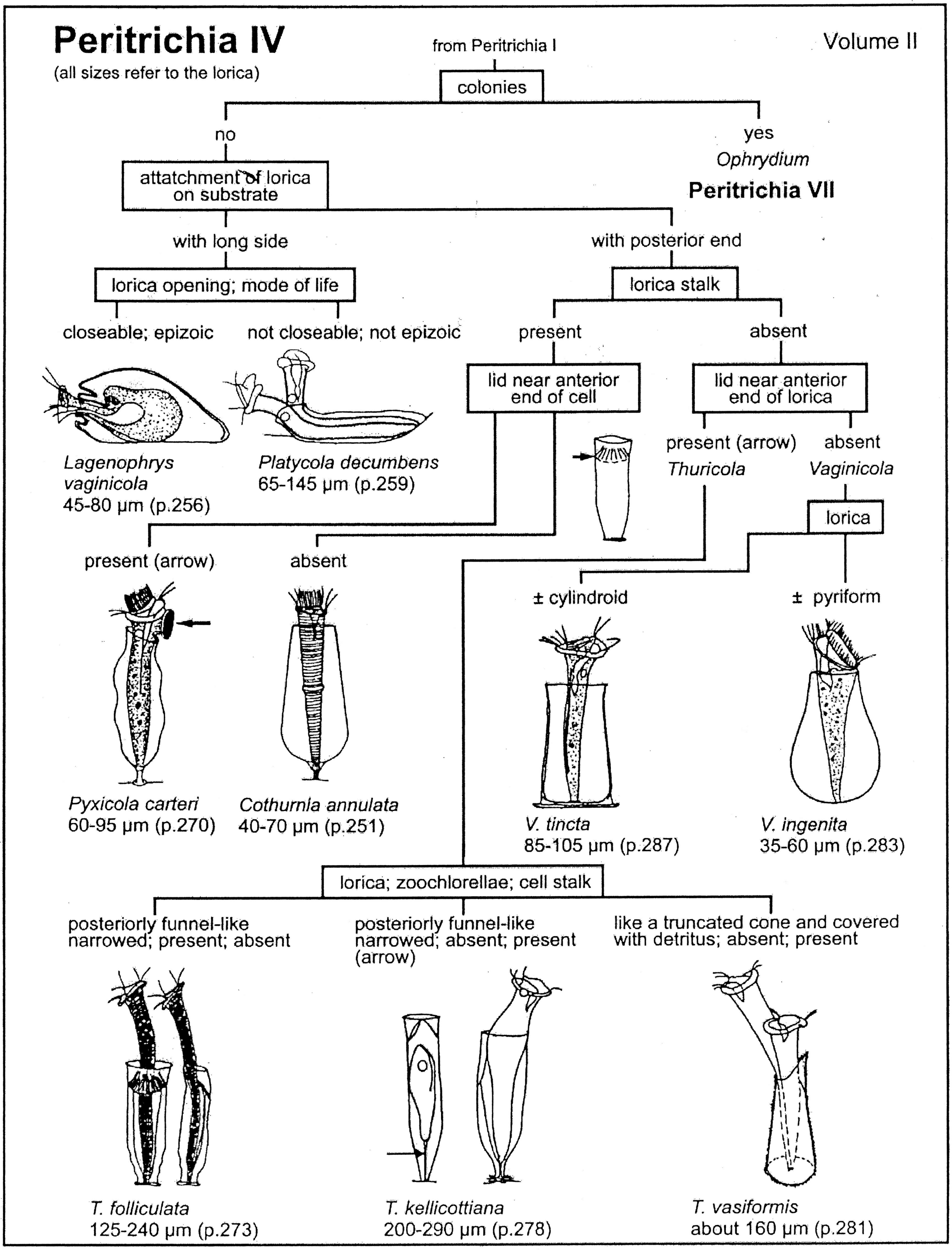
[2] The hyaline, gelatinous loricas of *Ophrydium* species are easily overlooked. Thus, follow key Peritrichia VII for very long and slender specimens.

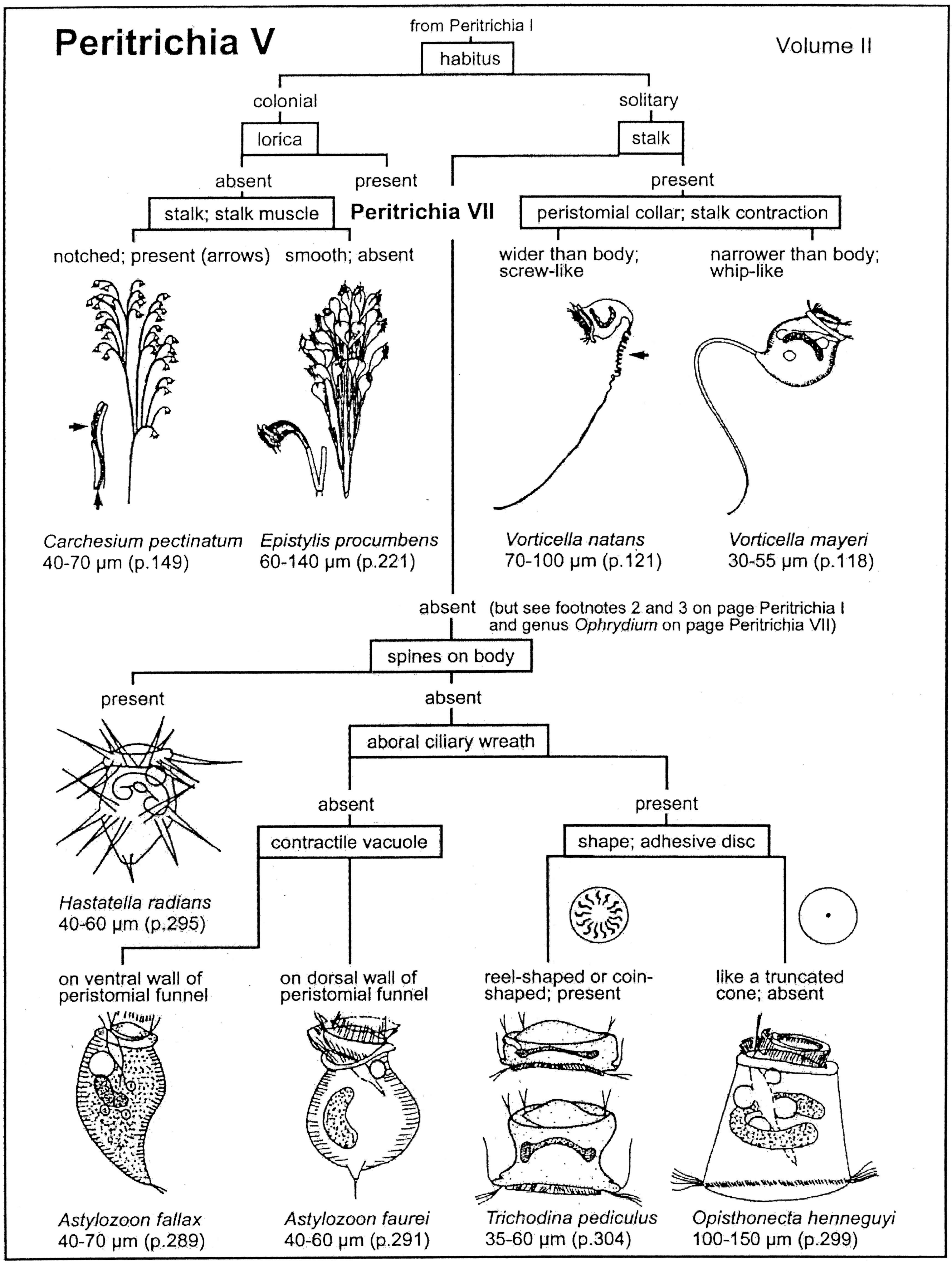
[3] Stalked species detach from the substrate with or without stalk and are then mobile, i.e. free-swimming too. Furthermore, all peritrichs can transform to mobile swarmers, which are difficult to separate from naturally stalkless species (see Peritrichia V, bottom). However, species of these genera (*Opisthonecta*, *Astylozoon*, *Hastatella*) are rare in running waters, usually occurring only in ephemeral and/or dammed waters. Many of the sessile species are sometimes attached on animals although being not true epizoons (e.g. *Carchesium polypinum*). Thus, if in doubt, first follow key Peritrichia VI; if it does not fit any of these species choose "sessile".

[4] Colony founders, which may occur in older samples, are solitary, i.e. not ramified. Pay attention to stalk diameter.


Peritrichia II
Volume II
from Peritrichia I
pellicle; contractile vacuole (CV)
with hyaline seam (arrows); 1
smooth or transversely striated; 1 or 2
with many tiny blisters; 2
Vorticella
granules on stalk muscle; contractile vacuole
conspicuous; 2 (arrows)
inconspicuous; 1
CV
CV
cytoplasm at X 100
colourless or yellowish
dark to black
Pseudovorticella chlamydophora
50-70 µm (p.125)
V. picta
50-70 µm (p.101)
Pseudovorticella monilata
50-70 µm (p.130)
macronucleus
J-shaped in longitudinal axis of cell
horseshoe-shaped in transverse axis of cell
oblique bulge near posterior end
present (arrow)
absent
macronucleus
V. campanula
60-90 µm (p.105)
V. marginata
70-90 µm (p.114)
V. fromenteli
70-90 µm (p.116)
horseshoe-shaped in transverse axis of cell
J-shaped or rod-like in longitudinal axis of cell
number of pellicular striae; body shape
macronucleus; body shape
< 30; pyriform
about 30-45; pyriform
about 35-45; slightly campanulate
rod-like; pyriform to slightly campanulate
J-shaped; usually distinctly campanulate
V. aquadulcis-complex
30-45 µm (p.59)
V. infusionum-complex
45-60 µm (p.64)
V. octava-complex
35-45 µm (p.75)
V. microstoma-complex, usually
< 60 µm (p.78)
V. convallaria-complex, usually
~ 60-80 µm (p.84)


Peritrichia III
from Peritrichia I
number of turns of adoral ciliary spiral on peristomial disc
Volume II
more than 3
less than 2
peristomial margin
with bulge
Epistylis
without bulge
Opercularia
stalk
usually distinctly annulated, 6 µm width
smooth, about 10 µm width
smooth, about 3 µm width
Campanella umbellaria
150-250 µm (p.225)
stalk
hollow
compact
peristomial collar
2 bulges
1 bulge
O. nutans
60-90 µm (p.176)
O. articulata
90-120 µm (p.172)
O. coarctata
40-65 µm (p.168)
macronucleus
horseshoe-shaped in transverse axis of cell
J-shaped in longitudinal axis of cell
E. chrysemydis
140-220 µm (p.182)
E. hentscheli
110-170 µm (p.201)
determination difficult! shape of cell; peristomial disc
E. galea
110-320 µm (p.196)
± cylindroid; umbilicated (arrow)
funnel-shaped; not umbilicated
club-shaped; not umbilicated
E. coronata
70-120 µm (p.188)
E. plicatilis
90-160 µm (p.205)
E. entzii
125-190 µm (p.190)


Peritrichia IV
(all sizes refer to the lorica)
from Peritrichia I
Volume II
colonies
no
yes
Ophrydium
Peritrichia VII
attatchment of lorica on substrate
with long side
with posterior end
lorica opening; mode of life
closeable; epizoic
not closeable; not epizoic
Lagenophrys vaginicola
45-80 µm (p.256)
Platycola decumbens
65-145 µm (p.259)
lorica stalk
present
absent
lid near anterior end of cell
lid near anterior end of lorica
present (arrow)
Thuricola
absent
Vaginicola
lorica
present (arrow)
absent
Pyxicola carteri
60-95 µm (p.270)
Cothurnia annulata
40-70 µm (p.251)
± cylindroid
± pyriform
V. tincta
85-105 µm (p.287)
V. ingenita
35-60 µm (p.283)
lorica; zoochlorellae; cell stalk
posteriorly funnel-like narrowed; present; absent
posteriorly funnel-like narrowed; absent; present (arrow)
like a truncated cone and covered with detritus; absent; present
T. folliculata
125-240 µm (p.273)
T. kellicottiana
200-290 µm (p.278)
T. vasiformis
about 160 µm (p.281)

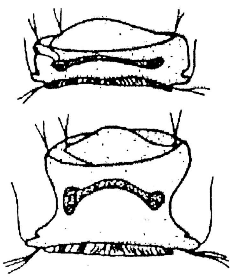

Peritrichia V
from Peritrichia I
Volume II
habitus
colonial
solitary
lorica
stalk
absent
present
present
stalk; stalk muscle
Peritrichia VII
peristomial collar; stalk contraction
notched; present (arrows)
smooth; absent
wider than body; screw-like
narrower than body; whip-like
Carchesium pectinatum
40-70 µm (p.149)
Epistylis procumbens
60-140 µm (p.221)
Vorticella natans
70-100 µm (p.121)
Vorticella mayeri
30-55 µm (p.118)
absent
(but see footnotes 2 and 3 on page Peritrichia I and genus Ophrydium on page Peritrichia VII)
spines on body
present
absent
aboral ciliary wreath
Hastatella radians
40-60 µm (p.295)
absent
present
contractile vacuole
shape; adhesive disc
on ventral wall of peristomial funnel
on dorsal wall of peristomial funnel
reel-shaped or coin-shaped; present
like a truncated cone; absent
Astylozoon fallax
40-70 µm (p.289)
Astylozoon faurei
40-60 µm (p.291)
Trichodina pediculus
35-60 µm (p.304)
Opisthonecta henneguyi
100-150 µm (p.299)

Peritrichia VI

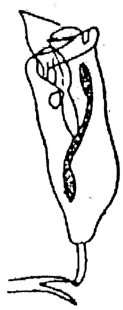
from Peritrichia I — Volume II

habitus

- **solitary** → **host**
  - hydrozoans, bryozoans, fishes
  - oligochaetes
  - small crustaceans
- **colonial** → **stalk**
  - annulated
  - smooth

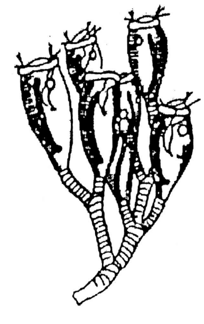


Trichodina pediculus
35-60 µm (p.304)

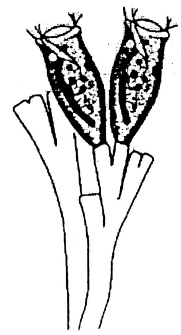


Rhabdostyla inclinans
45-80 µm (p.246)

Lagenophrys vaginicola
45-80 µm (p.256)



Epistylis digitalis
80-100 µm (p.212)



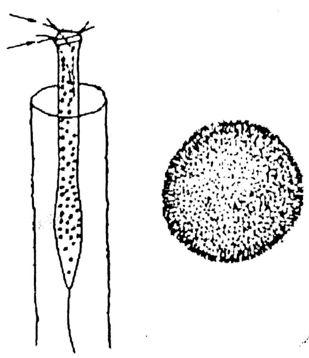
Epistylis nympharum
80-130 µm (p.217)

Peritrichia VII[1]

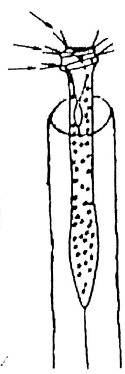
from Peritrichia IV, V — Volume II

zoochlorellae; colony size

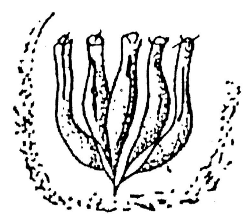
- **present; up to 10 cm** → **number of turns of adoral ciliary spiral on peristomial disc (arrows)**
  - 1 1/2
  - 2 1/2
- **absent; up to 3 mm** → **colony shape**
  - up to 5 individuals in cup-shaped, slimy lorica
  - hemispherical, up to 3 mm in size



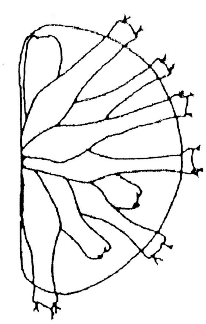
Ophrydium versatile
300-400 µm (p.232)



Ophrydium eutrophicum
250-350 µm (p.239)



Ophrydium crassicaule
180-200 µm (p.242)



Ophrydium sessile
280-320 µm (p.244)

[1] Often only stalkless, loricaless solitary specimens in running waters and plankton; then difficult to separate from *Gerda* spp., which lacks a lorica!

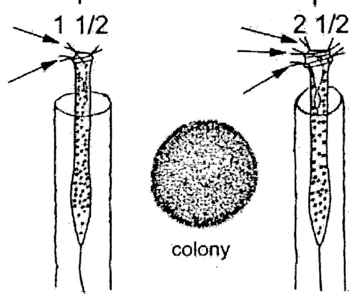
Peritrichia VIII (length without stalk)

Plankton Ciliates

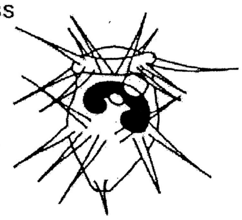
Identification of peritrichs usually requires live observation!

habitus

- large, green, globular or flabby and flattened colonies up to 15 cm across *Ophrydium*
  - **number of turns of adoral ciliary spiral on peristomial disc (arrows)**
    - 1 1/2: *O. versatile* 300–400 µm (p. 543)
    - 2 1/2: *O. eutrophicum* 250–350 µm (p. 540)



- with spines: *Hastatella radians* 40–60 µm (p. 460)

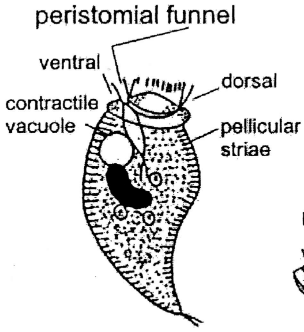


- different
  - **stalk**
    - present: Peritrichia IX
    - absent

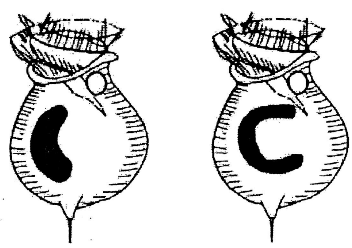
Actually, there is no character that would unequivocally sepa- rate stalkless peritrichs from swarmers of stalked species. Some experience is necessary, and look for stalked peritrichs at your site. Usually, swarmers have an aboral ciliary wreath, do not whirl food into buccal cavity and/or have the oral apparatus recessed and closed. If movement is slow and staggering and the peristome open, it may be a dying stalked peritrich.

aboral ciliary wreath (AW); bristles in centre of posterior end

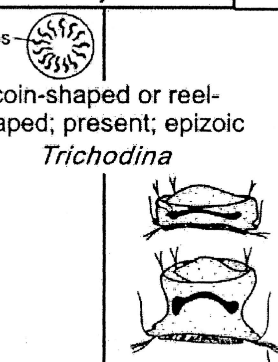
- absent; present[1]
  - **contractile vacuole**
    - on ventral wall of peristomial funnel: *Astylozoon fallax* 40–70 µm (p. 453)



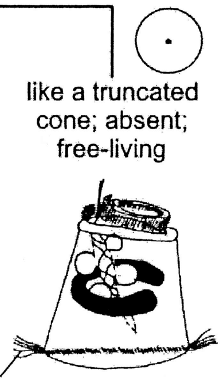
- on dorsal wall of peristomial funnel: *Astylozoon faurei* complex
  - **macronucleus**
    - reniform: *A. faurei* 35–65 µm (p. 455)
    - semicircular: *A. enriquesi* 35–65 µm (p. 455)



- present; absent
  - **shape; adhesive disc with denticles; life style**
    - coin-shaped or reel-shaped; present; epizoic: *Trichodina*



- **micronucleus; number of denticles in adhesive disc; host**
  - inconspicuous; 24–36; hydrozoans, bryozoans, fish: *T. pediculus* diameter 35–100 µm (p. 472)
  - conspicuous; 19–22; planktonic copepods: *T. domergue megamicronucleata* diameter 50–75 µm (p. 479) Species not treated in detail!
- like a truncated cone; absent; free-living: *Opisthonecta henneguyi*[2] 100–150 µm (p. 467)



[1] The bristles usually clearly separate *Astylozoon* spp. from swarmers of stalked peritrichs

[2] Easily confused with swarmes of stalked peritrichs; look for large oral apparatus, where the adoral ciliature makes 3–4 windings within buccal cavity (see introduction to group; p. 450). However, other *Opisthonecta* species have a normal-sized oral apparatus and are thus even more difficult to separate from swarmers of stalked peritrichs.

Peritrichia IX

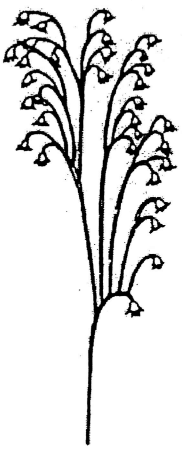
(length without stalk)

from Peritrichia VIII

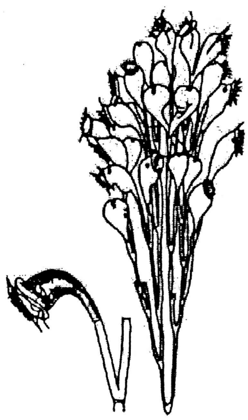
lorica

- present (usually hyaline or deserted and thus easily overlooked) *Ophrydium versatile* or *O. eutrophicum* (→ Peritrichia VIII)
  There are rather many loricate epiphytoplanktonic peritrichs (*Vaginicola*, *Thuricola*, ...), which are poorly known and were thus excluded from the book (for determination, consult KAHL 1935, SOMMER 1951, STILLER 1940, 1971)
- absent → **mode of life**
  - epiplanktonic, that is, attached to other planktonic organisms (or debris) Peritrichia X
  - euplanktonic, that is, not attached to other plankton organisms or debris[1] → **stalk**
    - branched (colonial) → **stalk; shape; zoochlorellae**
      - contractile; campanulate; absent
      - acontractile; campanulate; absent
      - acontractile; vase-shaped (globular when contracted); present
    - unbranched (solitary) → **shape; zoochlorellae; stalk**
      - vase-shaped; present; acontractile
      - campanulate or pyriform; absent; contractile → **peristomial collar; stalk contraction**
        - wider than body; srew-like (arrow)
        - narrower than body; whipe-like

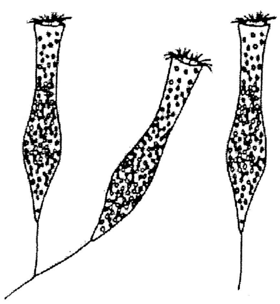
[1] Occasionally, epiplanktonic, colonial peritrichs detach with the stalk from the substrate. If in doubt, follow keys "Peritrichia X, XI"



Epicarchesium pectinatum
40–70 µm
(p. 508)

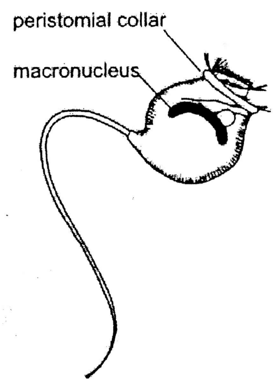


Epistylis procumbens
60–140 µm
(p. 527)

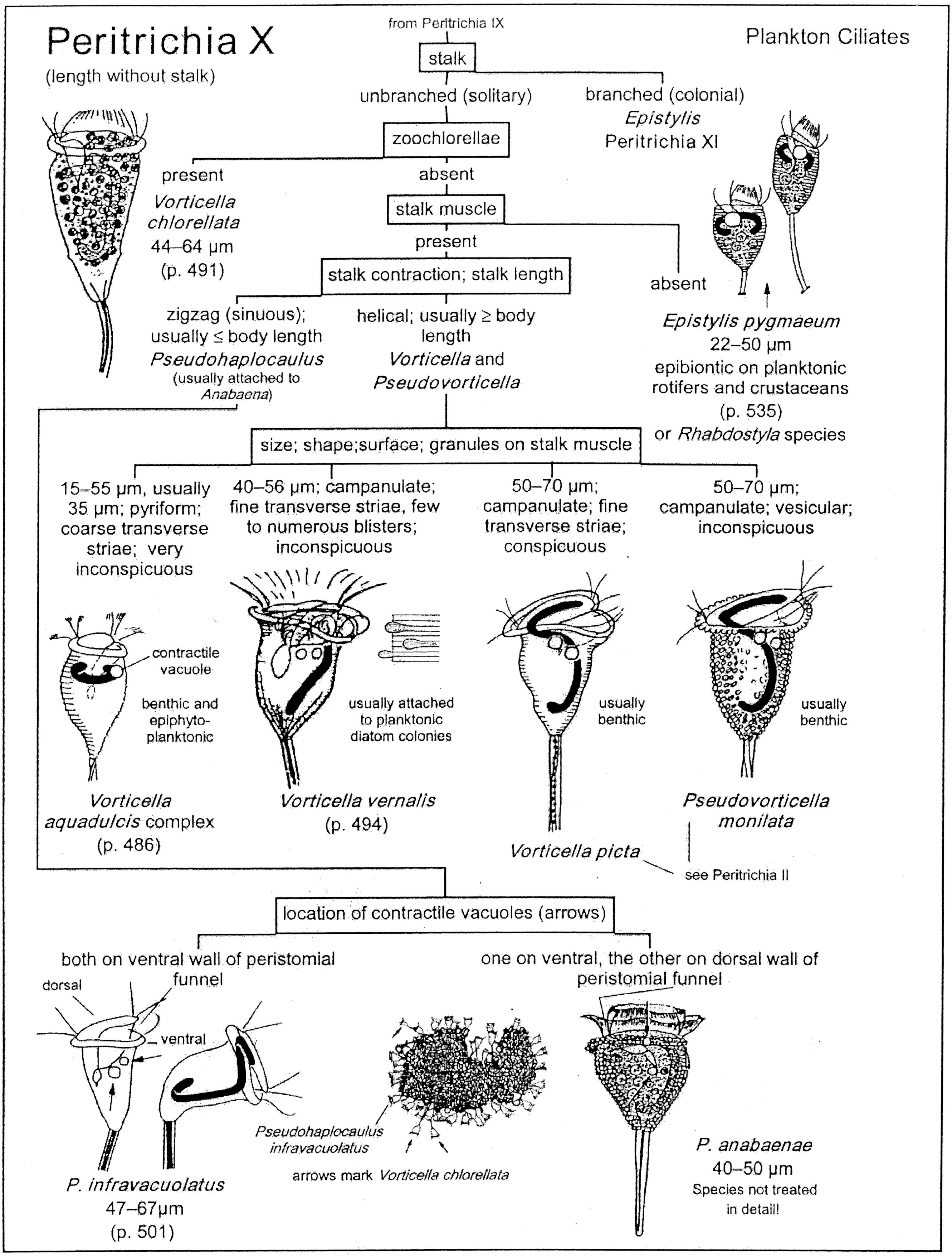


Ophrydium naumanni
solitary or in small colonies
40–50 µm
(p. 551)

Pelagovorticella natans
70–100 µm
(p. 482)



Pelagovorticella mayeri
30–55 µm
(p. 480)


Peritrichia X
(length without stalk)
from Peritrichia IX
stalk
unbranched (solitary)
branched (colonial)
Epistylis
Peritrichia XI
Plankton Ciliates
zoochlorellae
present
Vorticella chlorellata
44–64 µm
(p. 491)
absent
stalk muscle
present
absent
Epistylis pygmaeum
22–50 µm
epibiontic on planktonic rotifers and crustaceans
(p. 535)
or Rhabdostyla species
stalk contraction; stalk length
zigzag (sinuous); usually ≤ body length
Pseudohaplocaulus
(usually attached to Anabaena)
helical; usually ≥ body length
Vorticella and Pseudovorticella
size; shape;surface; granules on stalk muscle
15–55 µm, usually 35 µm; pyriform; coarse transverse striae; very inconspicuous
40–56 µm; campanulate; fine transverse striae, few to numerous blisters; inconspicuous
50–70 µm; campanulate; fine transverse striae; conspicuous
50–70 µm; campanulate; vesicular; inconspicuous
contractile vacuole
benthic and epiphyto-planktonic
usually attached to planktonic diatom colonies
usually benthic
usually benthic
Vorticella aquadulcis complex
(p. 486)
Vorticella vernalis
(p. 494)
Vorticella picta
Pseudovorticella monilata
see Peritrichia II
location of contractile vacuoles (arrows)
both on ventral wall of peristomial funnel
one on ventral, the other on dorsal wall of peristomial funnel
dorsal
ventral
Pseudohaplocaulus infravacuolatus
arrows mark Vorticella chlorellata
P. infravacuolatus
47–67µm
(p. 501)
P. anabaenae
40–50 µm
Species not treated in detail!

Peritrichia XI

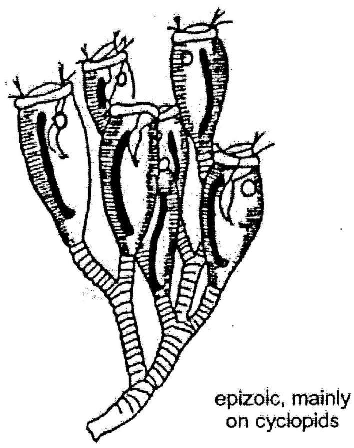
(length without stalk)

from Peritrichia X

stalk

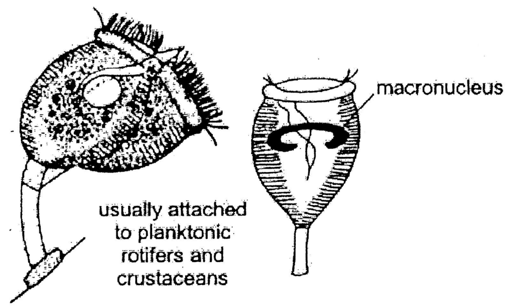
- annulated
- smooth → **size**
  - 22–50 µm
  - >60 µm → **size; stalk; shape**
    - 60–100 µm; 8–12 µm; funnel-shaped
    - >100 µm; 20–26 µm; barrel-shaped

annulated



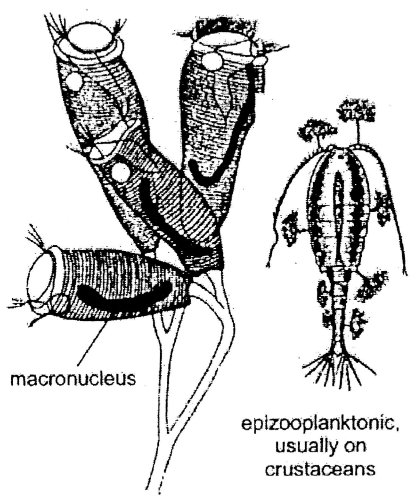
Epistylis digitalis
60–120 µm
(p. 523)

smooth – size – 22–50 µm



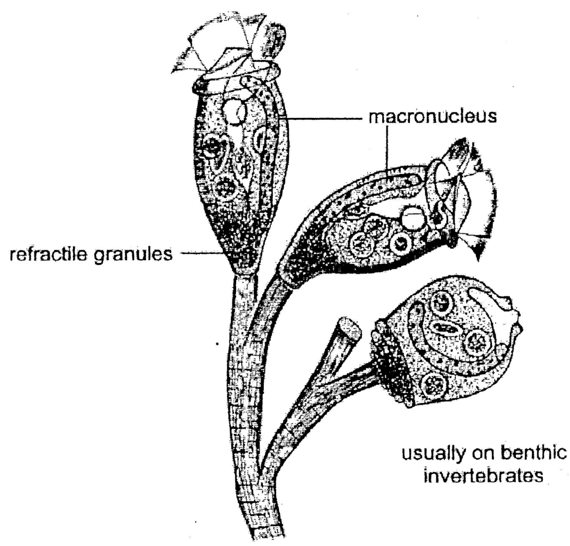
Epistylis pygmaeum
(p. 535)

>60 µm – size; stalk; shape – 60–100 µm; 8–12 µm; funnel-shaped



Epistylis anastatica
(p. 515)

>100 µm; 20–26 µm; barrel-shaped



Epistylis nympharum
(p. 521)
Species not treated in detail!

paroral membrane: → undulating membrane.
pellicle: "skin" of the ciliates, sensu lato identical with → cortex, sensu stricto with cell membrane and pellicular → alveoli.
peristome: ± → oral apparatus.
pharynx: throat; nonciliated tubular passeway leading from the → cytostome proper into the inner cytoplasm; typically, → food vacuoles are formed at its inner end; often strengthened by oral basket rods (nematodesmata, → oral basket) made of microtubules.
postoral: behind (underneath) of → oral apparatus.
preoral: in front (above) of → oral apparatus.
protargol: silver-protein-compound (→ silver impregnation).
reorganization band: special section in the → macronucleus of some ciliates (→ hypotrichs, → oligotrichs), involved in DNA replication and histone synthesis.
replication band: → reorganization band.
rhabdos: → oral basket.
scopula: stalk forming and attachment → organelle at posterior pole of → peritrichs. The analogous structure of stalked → suctorians is named scopuloid.
scutica: usually a small group of barren → basal bodies underneath the → oral apparatus; during → stomatogenesis, a part of the new → mouth is formed by this structure, which occurs only in the scuticociliates (for example, → *Histiobalantium*), a group of the → hymenostomes.
silver impregnation: cytological methods where silver ions (e.g. → protargol, silver nitrate) deposit onto argyrophilic sites (especially the → basal bodies) and which are then visible in the light microscope. For a detailed description of these methods, see FOISSNER et al. (1999).
silverline system: striated or reticulate cortical structure, which can be stained (impregnated) with silver nitrate (→ silver impregnation); usually composed of → fibres, and possibly involved in → morphogenetic processes and/or conduction of stimuli.
somatic: belonging to the body; as opposed to oral.
stomatogenesis: formation of the new → oral apparatus during cell division (→ morphogenesis).
suture: the linear space left between the ends of converging ciliary rows (for example, in front of and behind the → oral apparatus of → *Frontonia*).
swarmer: freely motile disperse stage in the life cycle of a number of sessile ciliates, for example, of → peritrichs and → suctorians.
symbiotic algae: single-celled algae living symbiotic in the ciliate cytoplasm (→ zoochlorellae).
toxicysts: → extrusomes filled with poison and used for capture of prey.
trichocysts: needle-shaped → extrusomes used for defence.
type species: species on which a genus is based; the sole species which cannot be removed from the genus.
undulating membrane (paroral membrane): one or several rows of narrowly spaced cilia, which usually adhere together at the right margin of the → oral apparatus; see also → endoral membrane.
vacuole: vesicle; → contractile vacuole and → food vacuole.
vestibulum: → buccal cavity.
zoochlorellae: → symbiotic algae of the genus *Chlorella*.
zooids: the individuals of → peritrichs with branched stalk.

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13 Sytematic Index

The index contains all scientific names mentioned in the flow charts. It is two-sided, that is, species appear both with the generic name first (if one knows only the genus name) and, more importantly, with the species-group name first (if one knows the species-group name but not the newest generic combination). Furthermore, all pages where a certain species is mentioned are indexed, which provides some sort of cross-referencing showing where the same species may be separately arrived at. Generic (for example, *Carchesium*) and species names (for example, *Carchesium polypinum*) appear in *italics*; suprageneric taxa (main groups, for example, **Peritrichia**) are given in boldface; communities (for example, Carchesietosum polypinae) are written in ordinary roman type.

A

8 Ecological summary of the species contained (Table)

Table 1 is a compilation of tables contained in FOISSNER et al. (1995, 1999). It orientates about live biomass (and thus much more useful than many literature data based on preserved and stored specimens), food (many species likely have a broader range), salinity tolerance, preferred water and habitat type, community allocation, and saprobic classification (re-assessed in the monographs cited and thus sometimes different from that contained in the key works by SLÁDEČEK (1973) and SLÁDEČEK et al. (1981).

Table 1: Ecological characterization of the species described in the Ciliate Atlas (FOISSNER et al. 1991, 1992, 1994, 1995) and the plankton book (FOISSNER et al. 1999). a = alphamesosaprobic, A = Aufwuchs (periphyton), Al = algae (except of diatoms, but inclusive autotrophic flagellates), b = betamesosaprobic, B = benthal, Ba = bacteria, Bo = terrestrial (mostly wetland) soils, BOD = influence of soil and/or moss, C = ciliates, CAR = Carchesietosum polypinae, COL = Colpidietum colpodae, Cy = cyanobacteria, CYR = Cyrtophoretea, e = eurysaprobic, EP = eupelagic, ECP = epiplanktonic on cyanobacteria, EPP = epiphytoplanktonic, EZB = epizoobenthic, EZP = epizooplanktonic, F = flowing waters, Fl = heteotrophic flagellates, Fs = anaerobic mud (and anaerobic zones in the pelagial), h = histophagous, HBE = high-load and/or oxygen deficient activated sludge, he = holo-euryhaline, i = isosaprobic, K = sewage-treatment works (activated sludge plants), Ki = diatoms, m = metasaprobic, M = mixotrophic, that is, autotrophic (due to symbiotic algae or sequestered chloroplasts) and heterotrophic, MAR = Marynetum, MET = Metopetum, MOO = mire influence, mpe = meso- to poly-euryhaline, mps = meso- to poly-stenohaline, NBE = normal activated sludge, O = omnivorous (feeds on autotrophic and heterotrophic protists, sometimes even on small metazoans), o = oligosaprobic, oe = oligo-euryhaline, OLI = Oligotrichetea (lake influence), ome = oligo- to meso-euryhaline, oms = oligo- to meso-stenohaline, os = oligo-stenohaline, p = polysaprobic, P = pelagial, pe = poly-euryhaline, PLE = Pleuronemetum coronatae, ps = poly-stenohaline, R = predacious (feeds on protozoa, mostly ciliates, some species even ingest small metazoans), Ro = rotifera, S = stagnant waters, Sb = sulphur bacteria, STE = Stentoretum, T = epizoic, TRI = Trithigmostometum cucullulae, x = xenosaprobic.

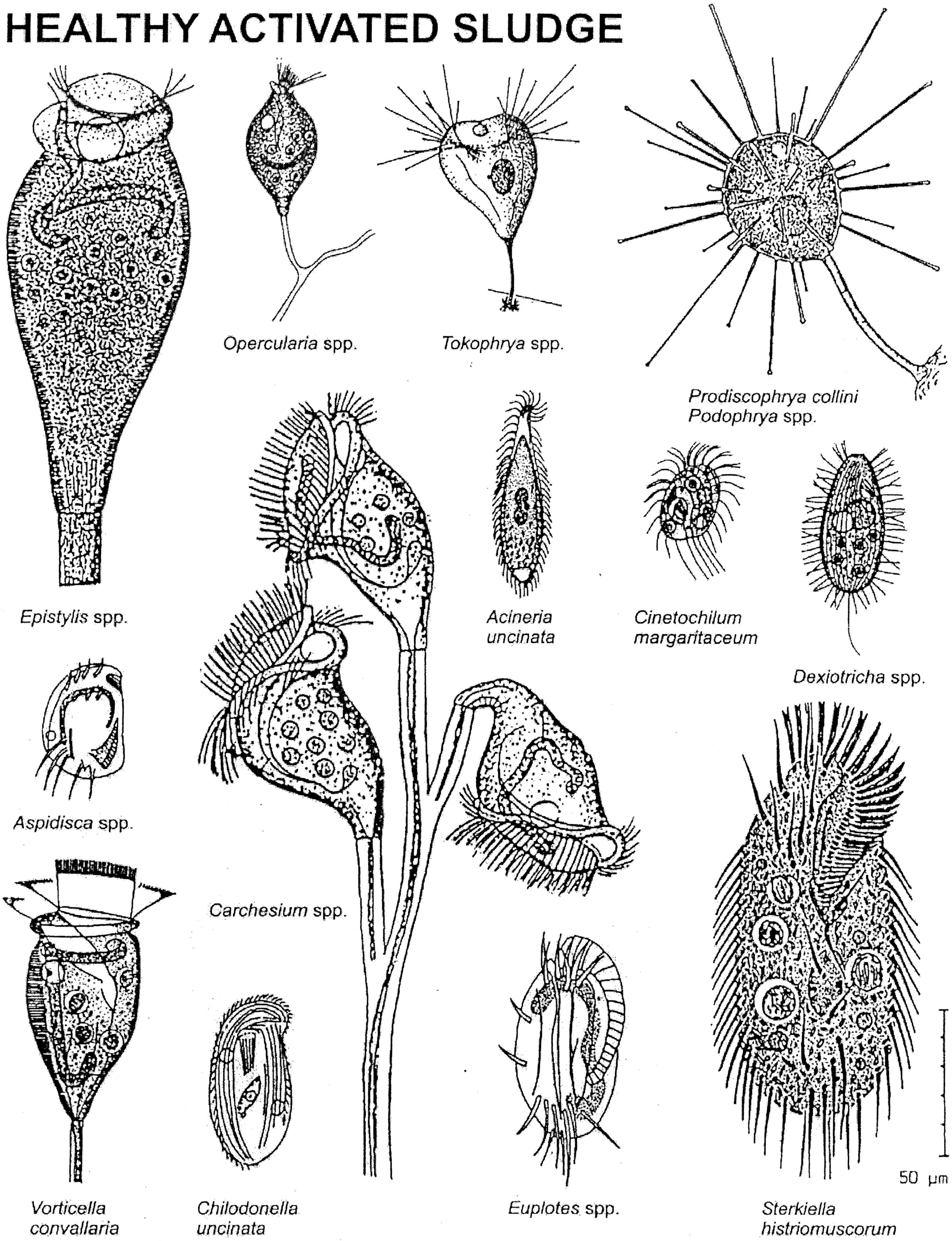
Species	Biomass (mg) of 10[6] ind.[(a)]	Main food	Salinity tolerance[(b)]	Occurrence			
				Preferred water type	Preferred habitat	Community[(c)]	Saprobity[(d)]
Acineria incurvata	55	R	he	F, S, K	A, B	COL, HBE	p–i
Acineria uncinata	10	R	os	F, S, K	A, B	COL, NBE	a–p
Acineta flava	30	R	oe?	F, S	A, T		b
Acineta grandis	150	R	oe?	F, S	A, T		b–o
Acineta tuberosa	20	R	he	S, F, K	A, T		a–b
Actinobolina radians	125	R	oe?	S, F	P, A, B	OLI	b
Actinobolina smalli	11	M, R	os	S	P, B	OLI	
Actinobolina vorax	250	R	oms?	S	EP, Bo	OLI	o
Actinobolina wenrichii	90	M, R	os	S	EP?	OLI	
Amphileptus carchesii	200	R	os	S, F	A	CAR	a
Amphileptus claparedii	60	R	he?	S, F	A	CAR	a
Amphileptus pleurosigma	150	R	oms	S, F	A, B	STE	b–a
Amphileptus procerus	160–1500	R	os	S, F	B		b–a
Amphileptus punctatus	80	R	os	S, F	A, B		a
Askenasia acrostomia	32	Al, C	os	S	EP	OLI	
Askenasia chlorelligera	20	M	os	S	EP	OLI	
Askenasia volvox	35	Al, Ki	oe?	S, F	P, B	OLI	b
Aspidisca cicada	10	Ba	he?	F, S, K	B, A	TRI, CYR, NBE	a–b
Aspidisca lynceus	17	Ba	ome?	F, S, K	B, A	TRI, CYR, NBE	b–a
Aspidisca turrita	7	Ba	he	F, S, K	B, A	NBE	a–b
Astylozoon fallax	30	Ba	os	S	EP	MAR, OLI	b–a
Astylozoon faurei	50	Ba	oms?	S, F	EP	MAR, OLI	b–a
Astylozoon faurei-complex	50	Ba	oms?	S, F	EP	MAR, OLI	b–a
Balanion planctonicum	0.3–3.6	Al, Ba	os	S	EP	OLI	o
Balantidion pellucidum	60	O	os	S	EP	OLI	
Belonophrya pelagica	11	Ro	os	S	EP	OLI	
Blepharisma coeruleum	250	Al (O)	os	S, F	B		b
Blepharisma lateritium	250	Ba, Al	os	S	B, P		b

Table 1. Microfaunal species and communities as indicators of sludge plant performance.

Organisms	Performance	Remarks	Literature[a)]
Species (usually when subdominant at least)			
Aspidisca cicada (Fig. 2)	Good	Stable plant conditions	1
Coleps hirtus	Good	Effective nitrification with good removal of ammoniacal-N in effluent	1
Enchelyomorpha vermicularis (Fig. 3)	Poor	Microaerobic; overloading; hydraulic problems	2, 3
Euplotes patella (Fig. 2)	Mediocre	When abundant and in connection with many rotifers indicative for an increasing sludge volume index; otherwise underload	2, 6
Holophrya discolor	Mediocre	Microaerobic; intermittent and very low oxygenation; high N-reduction	4
Litonotus lamella	Poor	Deficient sludge setting	
Litonotus obtosus	Poor	Poor sludge setting	16
Metopus spp. (Fig. 4)	Poor	Anaerobic conditions; overloading; hydraulic problems	1, 2, 5, 9
Plagiocampa rouxi	Mediocre	Microaerobic; intermittent and very low oxygenation; high N-reduction	4
Spirostomum teres (Fig. 3)	Mediocre	Microaerobic; intermittent and very low oxygenation; high N-reduction	4
Trimyema compressum (Fig. 3)	Poor	Microaerobic; overloading; hydraulic problems	2, 3
Vorticella campanula	Good	High effluent quality; underload	2, 10
Vorticella convallaria (Fig. 2)	Mediocre	Lack of nitrification	1
Vorticella convallaria and *Arcella hemisphaerica*	Good	High sludge retention time; underload	2, 16, 17
Vorticella microstoma/infusionum (Fig. 3)and *Opercularia* sp. (Fig. 3)	Poor	Low clearing efficiency, especially when connected with high flagellate abundance; anaerobic; high sludge load and sludge volume index	7, 8, 9, 17
Vorticella striata	Poor	Poor effluent quality	1
Communities (when dominant or subdominant)			
Small flagellates	Poor	Oxygen depletion; overloading; sludge maturation period; onset of nitrification	8, 18
Small naked amoebae and flagellates	Poor	Very high load; not easily degradable material; sludge maturation	8
Small flagellates, naked amoebae, swarmers of peritrich ciliates; many dispersed bacteria	Poor	Unstable sludge; sludge maturation; toxic influences	2, 9
Testate amoeba	Good	Underloading, high sludge retention time; usually found in N-removal plants	8
Testate amoebae; crawling ciliates; attached peritrich ciliates with width peristome; nematods; rotifers (Fig. 2)	Good	Healthy, low-loaded, sufficiently aerated and well-flocculated sludge with high effluent quality	12
Glaucoma, Dexiostoma campylum (Fig. 3), *Vorticella microstoma* and peritrich swarmers, flagellates and naked amoebae	Poor	Insufficient oxygenation; many dispersed bacteria; poor effluent	2, 9
Vorticella infusionum (Fig. 3); *Opercularia coarctata; Acineria uncinata* (Fig. 2); small flagellates	Poor	High-loaded with insufficient oxygen; shock-load; high ammonia; many dispersed bacteria	12
Heterotrich ciliates and many flagellates	Poor	Poor operation of RBC system	5
Epistylis, large naked amoebae, rotifers	Good	When in last stage of RBC system	13

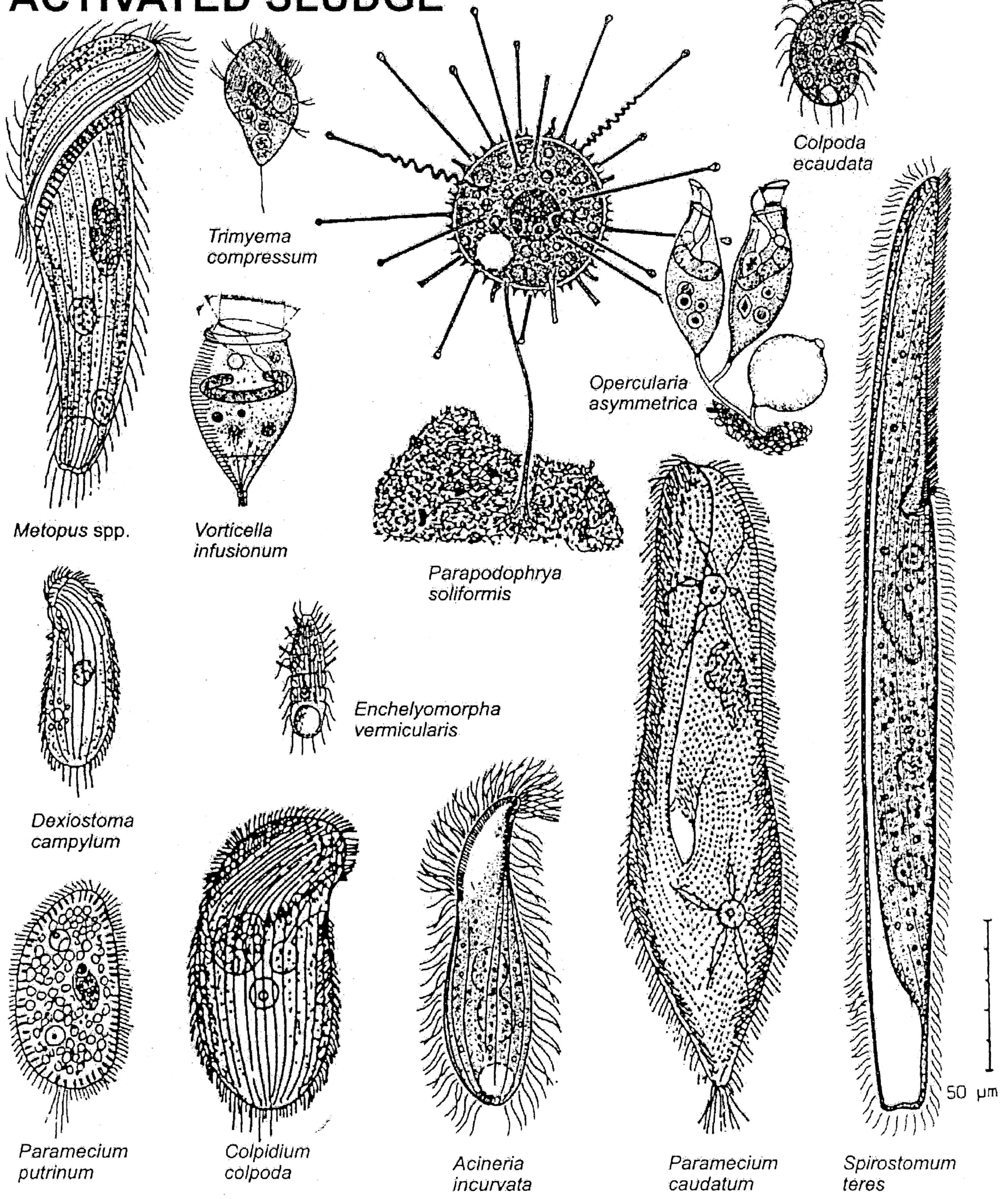
continued

HEALTHY ACTIVATED SLUDGE



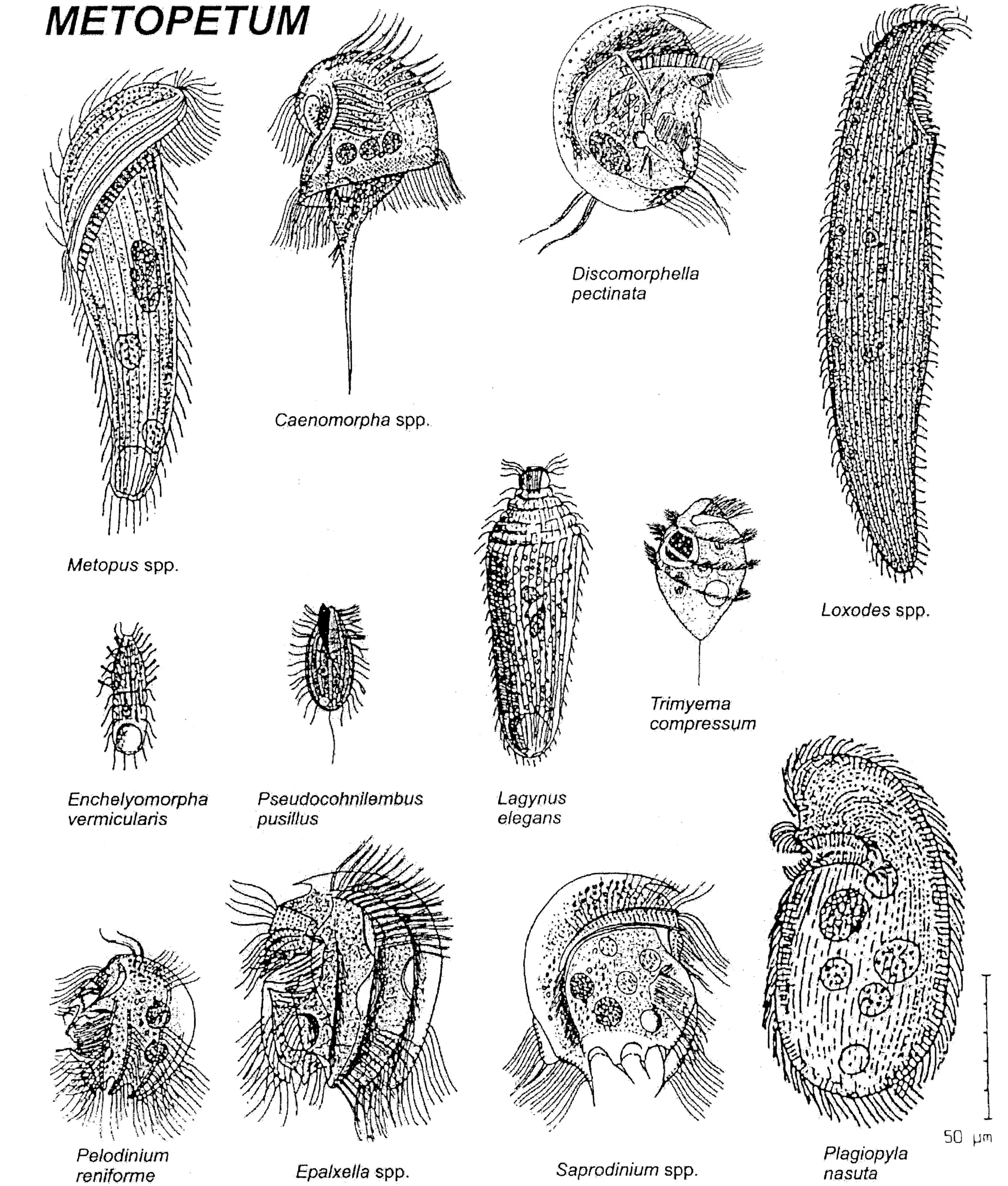
Ciliate community of healthy ("normal") activated sludge. An assortment of species usually occurring in moderately and heavily polluted (alpha-mesosaprobic to beta-mesosaprobic, alpha-mesosaprobic) running waters is found in "normal" activated sludge. The species of this community indicate sufficient oxygen supply and appropriate load. Often, ciliates achieve high abundances (> 10000 individuals / ml) and feed on bacteria, thereby reducing the turbidity of the effluent (Curds 1992). See Schleypen & Gschlössl (1992) for detailed advice on activated sludge investigation. Scale bar division 10 µm.

OVERLOADED AND/OR OXYGEN DEFICIENT ACTIVATED SLUDGE



Ciliate community of overloaded and/or oxygen deficient activated sludge. An assortment of species usually occurring in heavily and very heavily polluted (alpha-mesosaprobic to polysaprobic, polysaprobic) running waters is found in overloaded and/or oxygen deficient activated sludge. The species of this community indicate insufficient oxygen supply (*Vorticella infusionum*-complex, *Dexiostoma*), anaerobic conditions (e.g., *Metopus, Trimyema*) or overload (e.g., *Colpidium, Dexiostoma, Paramecium*). The effluent is often turbid because free bacteria are insufficiently eliminated. See Schleypen & Gschlössl (1992) for detailed advice on activated sludge investigation. Scale bar division 10 µm.

METOPETUM



Ciliate community of anaerobic mud (*Metopetum*). Indicator species are members of the genus *Metopus* (s.l.) and certain heterotrichs (all described in Vol. II). Most of the species belonging to the *Metopetum* are strictly bound to anaerobic conditions, i.e. oxygen is poisonous for them; they do not have mitochondria but hydrogenosomes and tolerate the richly occurring H_2S without damage. This community is often poor in species and individuals and feeds mainly on (sulphur) bacteria. The occurrence of one or several of these species in a sample is an unfailing indication of microaerobic or anaerobic conditions. Scale bar division 10 µm.

Table 1. (continued)

Organisms	Performance	Remarks	Literature[a)]
Green algae on plant wall	Good	Underload since a long time	9
Small swimming ciliates	Mediocre	Too short sewage retention time; insufficient oxygenation	8
Large swimming ciliates (Fig. 3)	Mediocre	Overloading; insufficient oxygenation	8
Crawling ciliates (abundance > 2000/ml)	Good	Sludge volume index < 200	8
Sessile and crawling ciliates	Good		8
Crawling and attached ciliates	Good	High ratio indicates good effluent	15
Sessile ciliates	Decreasing	Transient phenomena, such as recent sludge extraction, discontinuous load	8
Sessile ciliates	Good		1
Ciliates	Good	When abundance is 10^6/l or more	8
Ciliates	—	Abundance < 10^4 (poor), 10^4–10^6 (mediocre), > 10^6 (good)	11, 17
Metopetum (Fig. 4)	Poor	Anaerobic conditions; overload; hydraulic problems; putrefaction	2, 9
Swimming and attached ciliates	Mediocre	When highly diverse indicative for stable sludge but insufficient effluent quality	2, 9
Swimming ciliates	Mediocre	Often dominate in plants with short retention time; effluent mediocre; disappear after pH-shock	1, 18
Vorticella microstoma and *V. campanula*	Good	Well-setting sludge	10
Cyrtophorids, hypotrichs, scuticociliates, pleurostomatids (Fig. 2)	Good	Good operation of RBC system (Rotation Biological Contactor)	5
Opercularia, Uronema, nematods	Poor	Indicate overloading when in last stage of RBC system	13
Carnivorous ciliates, e. g., *Litonotus lamella, Amphileptus*	Poor	Poor-setting sludge	10
Aspidisca cicada, Chilodonella spp., *Vorticella striata* (Fig. 2)	—	High sludge retention time	10
Epistylis plicatilis and *Vorticella striata*	Decreasing	Indicate beginning sludge bulking when their abundances distinctly increase; high sludge volume index (SVI)	14

[a)] 1 = MARTIN-CERECEDA et al. (1996), 2 = FOISSNER et al. (1995), 3= PEREZ-UZ et al. (1998), 4 = GANNER et al. (2002), 5 = MARTIN-CERECEDA et al. (2001), 6 = CINGOLANI et al. (1991), 7 = GORI et al. (1991), 8 = MADONI (1994), 9 = SCHLEYPEN & GSCHLÖSSL (1992), 10 = LEE et al. (2004), 11 = DE MARCO et al. (1991), 12 = DRZEWICKI & KULIKOWSKA (2011); 13 = BERRI & CASASCHI (1991), 14 = HU et al. (2013); 15 = BEDOGNI et al. (1991), 16 = ZHOU et al. (2006), 17 = TOMAN (2002); 18 = CYBIS & HORAN (1997).

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