2 Microbiology of Composting

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List of Abbreviations

APPL	acid precipitable, polymeric lignin
CFU	colony forming unit
GC	gas–liquid chromatography
HDMF	3-hydroxy-4,5-dimethyl-2(5H)-furanone
MS	mass spectroscopy
PVC	polyvinyl chloride
SAR	systemic acquired resistance
TMV	tobacco mosaic virus
TOC	total organic compound
v.s.	volatile solids

1 Introduction

In his comprehensive monographs, HAUG (1980, 1993) defines composting as *"the biological decomposition and stabilization of organic substrates under conditions which allow development of thermophilic temperatures as a result of biologically produced heat, with a final product sufficiently stable for storage and application to land without adverse environmental effects"*. This definition differentiates composting from the mineralization of dead organic matter taking place in nature above the soil or in its upper layers leading to a more or less complete decomposition – besides the formation of humic substances; it thus describes the compost pile as a man-made microbial ecosystem. Composting has been carried out for centuries, originally as an agricultural and horticultural practice to recycle plant nutrients and to increase soil fertility (HOWARD, 1948); nowadays it has become also part of the management of waste disposal to get rid of the huge amounts of diverse organic waste produced by our civilized urban life. In most cases, the product *compost* has to be regarded as a by-product which hardly finances its production now often being carried out in highly mechanized plants (FINSTEIN et al., 1986; FINSTEIN, 1992; JACKSON et al., 1992; STEGMANN, 1996).

Composting has frequently been regarded as *more an art than a science*; this view, however, ignores the fact that its scientific base is well understood; of course, successful application of the principles requires experience as is more or less true for all applied sciences. In fact, the basic rules of composting have been known for decades as can be seen from numerous reviews and monographs of the last 25 years, beginning with UPDEGRAFF (1972) and ending with DE BERTOLDI et al. (1996). These surveys also indicate the broad interest of scientists of various disciplines in this process,

disciplines such as agriculture, horticulture, mushroom science, soil science, microbiology and sanitary engineering. The literature on composting is vast, comprising numerous broad reviews and minireviews of which only few can be cited in addition to those mentioned above: GASSER (1985), BIDDLESTONE et al. (1987), MATHUR (1991), MILLER (1991, 1993), HOITINK and KEENER (1993) and SMITH (1993); in addition, there exist also specific journals devoted solely or primarily to the subject, e.g., *"Compost Science"*, *"Agricultural Wastes"*, *"Müll & Abfall"*. Being well aware of the literature covered in these reviews, the author has tried to avoid repetition as much as possible; thus only selected papers will be considered, in addition to paying regard to some older work not reviewed until now because of its "hidden" publication.

This review is primarily concerned with the microbiology of composting. However, since composting touches many related disciplines, even the restriction to this selected field has to take various aspects into consideration which may seem at first glance rather remote from the composting process *per se*:

(1) The microbiology of self-heating of moist, damp organic matter has first been extensively studied in the case of agricultural products, e.g., hay, grain and wool. This phenomenon very early led to the concept of heat generation as part of microbial (and organismic in general) metabolism.
(2) The microbiology of composting is somehow related to soil microbiology and litter decomposition, i.e., soil fertility, turnover of organic matter in nature and formation of humic substances.
(3) The control of pathogenic agents in wastes to be composted, and the emission of pathogenic agents from compost plants are of concern to medical microbiologists. This aspect has to be extended to agents causing plant diseases and to the effect of compost on plant pathogens.
(4) Mushroom cultivation includes the preparation of a compost substrate, a special process whose study contributed much to the general understanding of composting.

The main focus of this chapter will be *the compost pile as a microbial ecosystem*, and a more proper title for it would be *"A Microbiologist's View of Composting"*. Most of the reviews cited above also deal with the microbiology of composting, and there are several which specifically discuss this aspect, e.g., FINSTEIN and MORRIS (1975) and LACEY (1980). Many papers mentioned there will not be cited in this review, and it is hoped that their authors will have some understanding for this approach: a reviewer has to make a selection of topics and of the literature to be cited, which inevitably leads to a somewhat personal view, not entirely free of bias.

2 Heat Production by Microorganisms

Any metabolism – from microbes to man – leads inevitably to the production of heat (Fig. 1, Tab. 1). This is actually a consequence of the 2nd law of thermodynamics, i.e., only part of the energy consumed can be transformed into *useful work*, e.g., biosynthesis, while the rest is liberated as heat to increase the entropy of the surroundings. Very often, mostly just for simplification, the degradation of a carbohydrate (e.g., glucose) serves as an example to demonstrate this context: Tab. 2 gives an energy balance for the aerobic metabolism of 2 M glucose, assuming that 1 of them enters the energy metabolism producing 38 ATP M^{-1} glucose, whereas the other supplies the precursors for the biosynthesis of new biomass which consumes the 38 ATP: According to this calculation, which follows the reasoning of DIEKERT (1997), the catabolism has a physiological efficiency of 61–69%, whereas the anabolism of only 40%. A very similar balance has been found by TERROINE and WURMSER (1922) for the mold *Aspergillus niger* as discussed in detail by BATTLEY (1987, pp. 108 ff): 59% of the energy (not weight!) of the glucose consumed were incorporated into new biomass (mycelium), whereas 41% were liberated as heat.

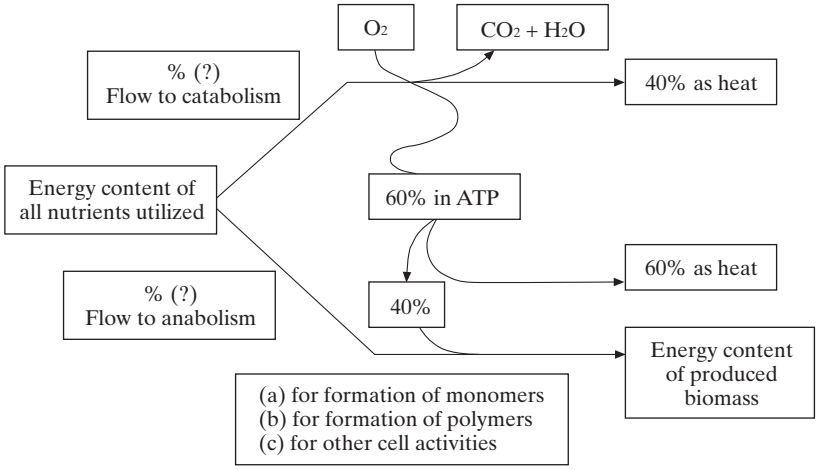

Fig. 1. Energy flow in aerobic metabolism of bacteria (for further explanation see text and Tab. 1).

Tab. 1. Energy flow in Microorganisms with Glucose as Substrate: Proportioning of the Substrate Energy to New Biomass and Liberated Heat as well as especially the Y_{ATP} Value Depend on the Number of ATP per Mol Glucose

	% Glucose Utilized for		% Substrate Energy in				
	Catabolism (Energy Production)	Anabolism (Biosynthesis)	New Biomass	Liberated Heat	ATP Glucose^{-1}	Y_s	Y_{ATP}
A	25	75	81.1	18.9	38	0.565	10.7
B_1	33.33	66.66	74.8	25.2	38	0.502	7.137
B_2	33.33	66.66	72.2	27.8	26	0.502	10.43
C_1	50	50	62.2	37.8	38	0.376	3.568
C_2	50	50	58.3	41.7	26	0.376	5.215

Tab. 2. Energy Balance of the Aerobic Metabolism of Glucose by Bacteria (Free Energy of Hydrolysis $ATP + H_2O \rightarrow ADP + P_i$: A = 52 kJ, B = 46 kJ)

Metabolism	A	B
Catabolic metabolism		
$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$	$\Delta\ G^{0_1} = -2{,}872$ kJ	
Invested into 38 ATP (38 · 52 or 46 kJ)	1,976 kJ = 69%	1,748 kJ = 61%
Liberated as heat	896 kJ = 31%	1,124 kJ = 39%
Anabolic metabolism		
Free energy of hydrolysis of 38 ATP	$\Delta\ G^{0_1} = -1{,}976$ kJ	
Invested in biosynthesis, transport, movement	790 kJ = 40%	699 kJ = 40%
Liberated as heat	1,186 kJ = 60%	1,049 kJ = 60%
Total balance		
2 M glucose (2 · 2,872)	$\Delta\ G^{0_1} = -5{,}744$ kJ	
Liberated as heat	2,082 kJ = 36%	2,173 kJ = 38%
Fixed in new biomass	3,662 kJ = 64%	3,571 kJ = 62%

Note that the heat of combustion of 1 M glucose amounts to $\Delta\ H_c = -2{,}816$ kJ.

The percentages of the substrate (1) employed for energy formation (catabolism) and (2) utilized for biosynthesis depend on the energy source and the kind of metabolism, (e.g., amount of ATP M^{-1} substrate).

For *E. coli* (26 ATP M^{-1} glucose) DIEKERT (1997) proposed the following balance: One third of the substrate (glucose) is used for the production of ATP, whereas two thirds [more correctly 4 of the 6 carbon atoms (Eq. 1)] appear in the biomass; this results in an Y_s of about 0.5 and an Y_{ATP} of about 10 (Tab. 3).

The heat produced in the metabolism of microbes cultivated on a small scale is rapidly dissipated to the environment and hardly noticed in laboratory experiments. Therefore, this phenomenon, although of great theoretical importance, is surprisingly not discussed in most textbooks of microbiology, a rare exception being the one by LAMANNA and MALLETTE (1959, pp. 586–589). Of course, heat production is of great practical significance in the mass culture of microorganisms and, therefore, treated in books on biochemical engineering, e.g., BAILY and OLLIS (1977, pp. 473–482) and CRUEGER and CRUEGER (1984, pp. 58–59); it has been extensively discussed by LUONG and

Tab. 3. Equations of Microbial Growth Calculated for Various Growth Efficiencies

(1)	$C_6H_{12}O_6 + 0.8\ NH_3 + 2.0\ O_2 \rightarrow 0.8\ [C_5H_7O_2N] + 2.0\ CO_2 + 4.4\ H_2O$	$Y_s = 90.4/180 = 0.502$
(2)	$C_6H_{12}O_6 + 0.7\ NH_3 + 2.5\ O_2 \rightarrow 0.7\ [C_5H_7O_2N] + 2.5\ CO_2 + 4.6\ H_2O$	$Y_s = 79.1/180 = 0.430$
(3)	$C_6H_{12}O_6 + 0.6\ NH_3 + 3.0\ O_2 \rightarrow 0.6\ [C_5H_7O_2N] + 3.0\ CO_2 + 4.8\ H_2O$	$Y_s = 67.8/180 = 0.376$
(4)	$C_6H_{12}O_6 + 0.5\ NH_3 + 3.5\ O_2 \rightarrow 0.5\ [C_5H_7O_2N] + 3.5\ CO_2 + 5.0\ H_2O$	$Y_s = 56.5/180 = 0.314$
(5)	$C_6H_{12}O_6 + 0.4\ NH_3 + 4.0\ O_2 \rightarrow 0.4\ [C_5H_7O_2N] + 4.0\ CO_2 + 5.2\ H_2O$	$Y_s = 45.2/180 = 0.251$
(6)	$C_6H_{12}O_6 + 0.3\ NH_3 + 4.5\ O_2 \rightarrow 0.3\ [C_5H_7O_2N] + 4.5\ CO_2 + 5.4\ H_2O$	$Y_s = 33.9/180 = 0.188$
(7)	$C_6H_{12}O_6 + 0.2\ NH_3 + 5.0\ O_2 \rightarrow 0.2\ [C_5H_7O_2N] + 5.0\ CO_2 + 5.6\ H_2O$	$Y_s = 22.6/180 = 0.125$

HAUG (1993, p. 248) considered $Y_s = 0.1$–0.2 as a typical growth yield in composting; for $Y_s = 0.1$ he presented the following balance (here reduced to one mole of glucose).

(8)	$C_6H_{12}O_6 + 0.16\ NH_3 + 5.2\ O_2 \rightarrow 0.16\ [C_5H_7O_2N] + 5.2\ CO_2 + 5.7\ H_2O$	$Y_s = 18.8/180 = 0.104$

1. Note: Calculation in g (NB = New Biomass)

(a) Complete oxidation of glucose without production of biomass
100 g glucose + 106,7 g O_2 → 146.7 g CO_2 + 60 g H_2O

(b) Eqs. (1) and (6) from above in g:
$Y_s = 0.502$: [100 + 7.5] substrate + 35.6 O_2 → 50.2 NB + 48.9 CO_2 + 44.0 H_2O
$Y_s = 0.188$: [100 + 2.8] substrate + 80.0 O_2 → 18.8 NB + 110.0 CO_2 + 54.0 H_2O

(c) The following equation has been used for the hypothetical composting process discussed in Sect. 9 (Fig. 15 and Tab. 15, Equ. 8a
$Y_s = 0.2008$: [100 + 3.02] substrate + 78.22 → 20.08 NB + 107.56 CO_2 + 53.6 H_2O

2. Note Calculation of oxygen consumption in relation to loss of volatile solids, Δ v.s., in g:
$Y_s = 0.502$: Δ v.s. = 107.5 − 50.2 = 57.3 + 35.6 O_2 → 48.9 CO_2 + 44.0 H_2O
Δ v.s. : 100 + 62.13 O_2 → 85.34 CO_2 + 76.79 H_2O
$Y_s = 0.188$: Δ v.s. = 102.8 − 18.8 = 84.0 + 80.0 O_2 → 110.0 CO_2 + 54.0 H_2O
Δ v.s. : 100 + 95.23 O_2 → 130.95 CO_2 + 64.28 H_2O
$Y_s = 0.167$: Δ v.s. = 102.5 − 16.7 = 85.8 + 83.0 O_2 → 114.1 CO_2 + 54.7 H_2O
Δ v.s. : 100 + 96.73 O_2 → 132.98 CO_2 + 63.75 H_2O

VOLESKY (1983), in the monograph by BATTLEY (1987) and in Vol. 1 of the Second Edition of *Biotechnology* by POSTEN and COONEY (1993, pp. 141–143).

3 The Phases of the Composting Process

If the heat produced by the metabolism of microorganisms is prevented by some kind of insulation from being dissipated to the environment, the temperature of the habitat increases. This is the case when damp organic matter is collected in bulky heaps or kept in tight containers, as it is done when organic waste is composted either in large piles (windrows) or in boxes of various kinds. If the composting process is carried out as a batch culture – as opposed to a continuous operation – it proceeds in various more or less distinct phases which are recognized superficially by the stages of temperature rise and decline (Fig. 2). These temperature phases are, of course, only the reflection of the activities of successive microbial populations performing the degradation of increasingly more recalcitrant organic matter.

As shown in Fig. 2, the time–temperature course of the composting process can be divided into 4 phases:

(1) During the first phase a diverse population of mesophilic bacteria and fungi proliferates, degrading primarily the readily available nutrients and thereby raising the temperature to about 45 °C. At this point their activities cease, the vegetative cells and hyphae die and eventually lyse, and only heat resistant spores survive.
(2) After a short lag period (not always discernible) there occurs a second more or less steep rise of temperature. This second phase is characterized by the development of a thermophilic microbial population comprising some bacterial species, actinomycetes and fungi. The temperature optimum of these microorganisms is between 50 and 65 °C, their activities terminate at 70–80 °C.
(3) The third phase can be regarded as a stationary period without significant changes of temperature because microbial heat production and heat dissipation balance each other. The microbial population continues to consist of thermophilic bacteria, actinomycetes, and fungi.
(4) The fourth phase is characterized by a gradual temperature decline; it is best described as the maturation phase of the composting process. Mesophilic microorganisms having survived the high temperature phase or invading the cooling down material from the outside succeed the thermophilic ones and extend the degradation process as far as it is intended.

Fig. 2 presents just one of numerous examples of the temperature course that can be found in the literature, very typical ones having been published by CARLYLE and NORMAN (1941), WALKER and HARRISON (1960), NIESE (1959). In all cases the 4 phases mentioned have been observed more or less distinctly leaving no doubt that they characterize very closely the composting process.

Since the optimum temperature for composting is regarded to be about 50–60 °C, measures are being taken to prevent further self-heating except for a rather short period up to 70 °C to guarantee the elimination of pathogens (see Sect. 7.1). However, 70 °C appears to be not the limit of microbial heat production which can easily reach 80 °C as practised in the Beltsville process (see Sect. 4.3). Under certain conditions even much higher temperatures leading to ignition can be reached, but neither the exact requirements for such an event nor the mechanism of ignition appear to be well understood (BOWES, 1984). Whereas there are only rare cases of self-ignition of manure piles or compost heaps (JAMES et al., 1928), this phenomenon is not uncommon in the storage of damp hay (GLATHE, 1959, 1960; CURRIE and FESTENSTEIN, 1971; HUSSAIN, 1972) and fat contaminated pie wool (WALKER and WILLIAMSON, 1957).

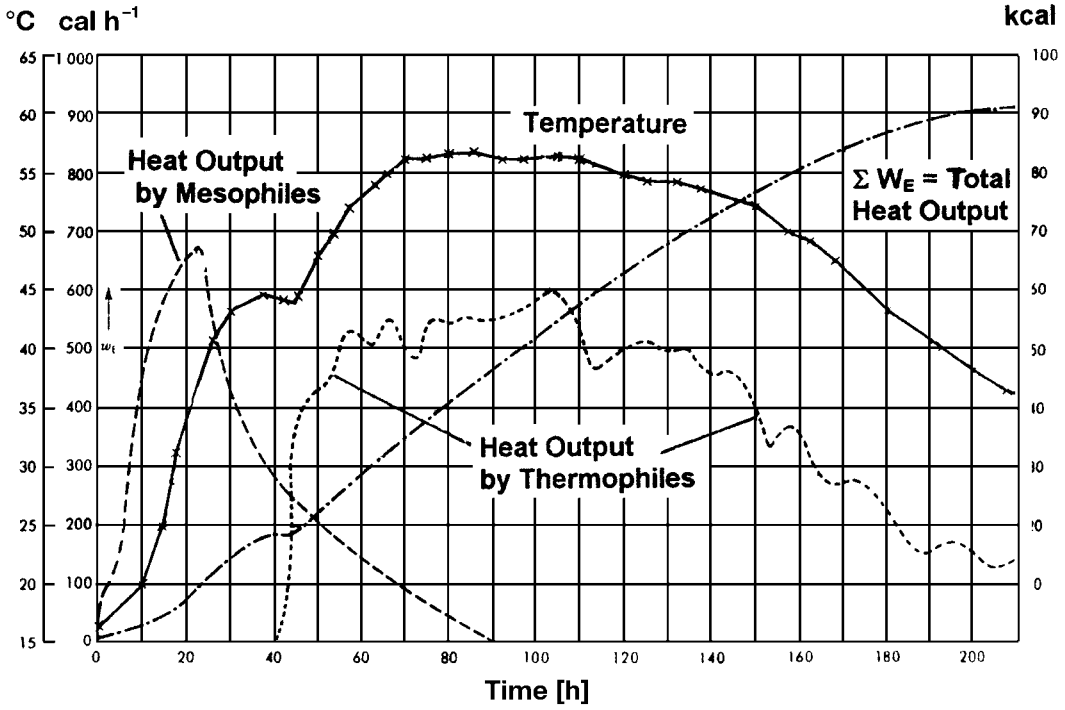

Fig. 2. Temperature course during the composting of urban garbage: four phases, *mesophilic, thermophilic, stationary*, and *maturation*, can easily be recognized (from PÖPEL, 1971).

As mentioned above the temperature phases are just a reflection of the activities of successive microbial populations. This has been demonstrated by various means – besides by a detailed analysis of the bacterial, actinomycete and fungal population:

(1) Fig. 3, taken from NIESE (1969), shows that the microbial community of fresh refuse plus sewage sludge exhibits a respiratory activity only at 28 and 38 °C, i.e., it consists primarily of mesophiles. On the contrary, the samples taken from the self-heated material started instantaneously to take up oxygen when incubated at 58 and 48 °C; the relatively high respiration rate at 38 °C is probably due to the broad temperature range of several thermophiles (Sect. 6, Fig. 8, Tab. 9).

(2) Fig. 4, taken from FERTIG (1981), illustrates the O_2 uptake and CO_2 production during the temperature course of composting: 4 maxima of microbial activity can be observed, surprisingly within the very short time of 54 h. Two or three maxima of CO_2 evolution during composting have been observed by numerous authors, e.g., SIKORA et al. (1983) who discussed also earlier observations of this kind; VIEL et al. (1987) reported three maxima of oxygen consumption.

(3) Finally, a detailed analysis of adaptation and succession of microbial populations in composting of sewage sludge has been undertaken by MCKINLEY and VESTAL (1984, 1985a,b), the main aim of their study being to ascertain the optimal temperature for the composting process: The microbial communities from hotter samples were better adapted to higher temperatures than those from cooler samples and *vice versa*, as

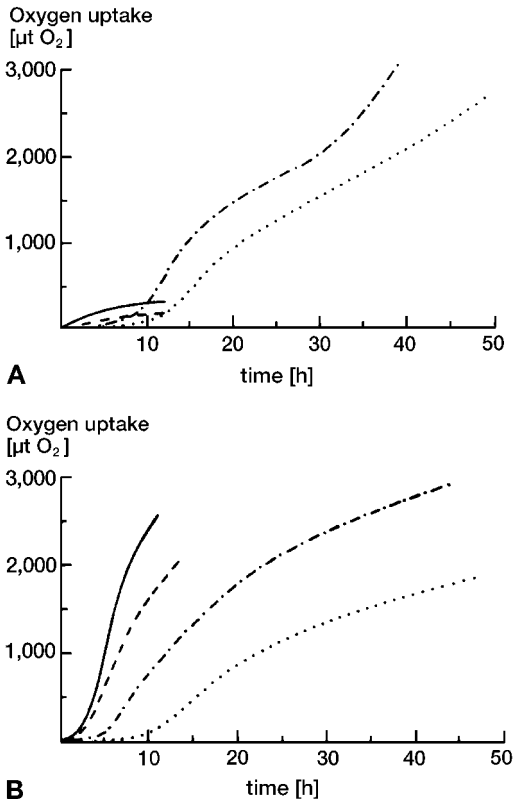

Fig. 3a,b. Oxygen uptake of microbial communities in Warburg flasks at different temperatures: **A** fresh garbage plus sewage sludge, **B** composting material removed from the pile during the high temperature phase, ····· 28 °C —·— 38 °C - - - - - 48 °C —— 58 °C (according to NIESE, 1969).

shown by the determination of the rate of [^{14}C]-acetate incorporation into cellular lipids and calculation of its apparent energies of activation and inactivation. Lipid phosphate was used as indicator of viable bacterial biomass. The authors came to the conclusion, that the composting temperature should not be allowed to exceed 55 °C – in agreement with numerous other investigators.

4 The Compost Pile as a Microbial Habitat

In order to secure fast stabilization of the waste material, the microorganisms performing this task have to be provided with *nutrients, water* and *oxygen*. Of course, the demand for nutrients appears to be contradictory since material without nutrients does not need to be stabilized. However, because organic waste material in any case lends itself to decomposition the nutritional state of the starting material deserves consideration.

A fourth parameter of composting is the *temperature*, which plays actually a dual role in this habitat: It is the result of microbial activity – without necessity of being taken care of at the commencement of the process – and at the same time it is a selective agent determining the microbial population at any stage of the composting process, eventually demanding its regulation by technical measures.

Finally, the *pH* of the habitat can be considered as environmental factor.

It is obvious that the various parameters are intimately related; this should be kept in mind when in Sects. 4.1–4.5 they are necessarily treated separately.

4.1 Organic Wastes as Nutrients

Waste suitable for composting comes from very diverse sources: grass clippings, leaves, hedge cuttings, food remains, fruit and vegetables waste from the food industry, residues from the fermentation industry, solid and liquid manure from animal houses, wastes from the forest, wood and paper industries, rumen contents from slaughtered cattle and sewage sludge from wastewater treatment plants. Thus, the starting material of composting varies tremendously in its coarse composition, and in addition there is often a seasonal variation of the material arriving at the compost plant. Since many of the materials listed above cannot be easily composted if supplied by themselves alone because of nutritional and/or structural reasons (water content), they have

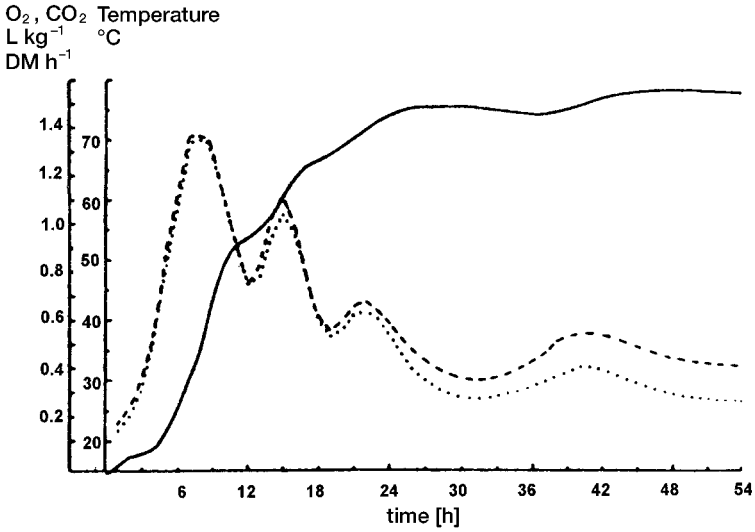

Fig. 4. Oxygen uptake and CO_2 production during laboratory composting: four maxima occurring within the first 2 d (!) are easily recognized (according to FERTIG, 1981).

to be mixed purposely if they are not delivered as a mixture in the first place.

Tables listing the chemical composition of the materials mentioned, e.g., contents of carbohydrates, proteins, fat, hydrocarbons, lignin and ash are given by BIDLINGMAIER (1983), and KROGMANN (1994), and can be found in various reviews cited above. Unfortunately, the data of most of the ingredients are rather incomplete making a strict comparison difficult. These tables sometimes contain empirical formulae of the substrates involved, e.g., for sewage sludge [$C_{10}H_{19}O_3$], for the organic fraction of domestic garbage [$C_{64}H_{104}O_{37}N$] for residues from vegetables [$C_{16}H_{27}O_8N$], and for grass [$C_{23}H_{38}O_{17}N$]. However, these figures are almost meaningless, except that they indicate the carbon–nitrogen ratio (see also Sect. 9.1, Tab. 16).

Of greater relevance is the *biochemical composition* of the various waste materials because this determines their susceptibility to microbial degradation. Those wastes containing carbohydrates, lipids and proteins, would be the most suitable carbon and energy sources for microbes, whereas materials with a high lignocellulose fraction and a shortage of nitrogenous compounds will be only slowly degraded. In fact, the biodegradability of organic matter in composting may be related to the lignin content (HAUG, 1993, pp. 312–314) employing a formula which has been derived originally for anaerobic digestion by CHANDLER et al. (1980):

biogradable fraction of volatile solids (v.s.) = 0.830–0.028 x lignin content in % of v.s. (9)

According to this formula a substrate containing no lignin would only achieve a maximum degradability of 83% because the decomposition of the substrate organics is coupled with production of bacterial by-products, some of which themselves are not readily degradable. However, since the waste material has to support the growth of several successive microbial populations, which have different nutritional requirements and different capabilities to attack macromolecules of organismic origin, the waste material need not (and, in fact, should not) consist solely of easily degradable materials.

It can be more or less safely assumed that the starting materials – at least mixtures of those listed above – contain the essential nutrients or elements for microbial growth. Whereas carbon compounds for energy metabolism and biosynthesis are in most cases in excess, the nitrogen supply is usually rather limited. In fact, the carbon–nitrogen ratio is considered a significant criterion of the starting material as well as of the product compost. A rule of thumb says that the C–N ratio at the beginning of composting should be about 30:1 and will be reduced to about 10:1 in the course of the process. Of course, there is a theory behind this empirical recommendation which has been seldom considered: The decrease of the C–N ratio can only be understood if we assume that there are several microbial populations, each deteriorating at the end of its growth phase and supplying its nitrogen to the next population. The factor by which this process advances depends on three parameters:

(1) the C–N ratio of the new biomass,
(2) the yield coefficient Y_s, and
(3) the rate of turnover of the biomass; the latter is, however, a matter of conjecture.

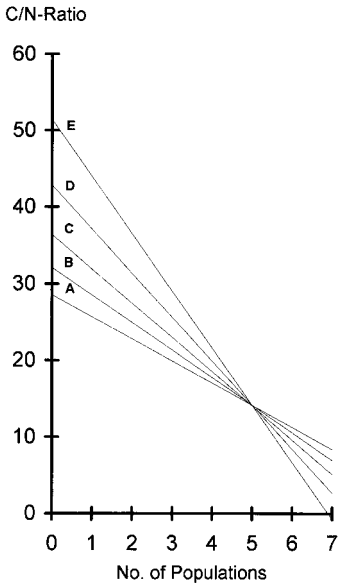

Fig. 5. The stepwise decrease of the C–N ratio by succeeding populations of bacteria (carbon turnover rate of the cell biomass=75%), values see Tab. 4.

In Fig. 5, Tab. 4 a bacterial biomass of $[C_5H_7O_2N]$ is assumed (C–N ratio 4.28), and a C turnover rate of 75%; the calculation has been carried out for seven yield coefficients, using the conception depicted in Tab. 5.

As mentioned above, the rate of biomass turnover is open for discussion. However, whichever reasonable value will be employed, the result will correspond to Fig. 5, Tab. 3, only the slope of the straight lines varying. From this figure it can be deduced that at $Y_s = 0.5$ four succeeding populations reduce the C–N ratio from 25.7–12.8; at the same time, they decompose 50% of the organic matter. The same calculation can be done with fungal biomass $[C_{10}H_{18}O_5N]$, C–N ratio = 8.57: In this case,

Tab. 4. Stepwise Decrease of the C–N Ratio by Succeeding Populations of Bacteria (Fig. 5)

	Y_s	Decrease per Population Δ Volatile Solids (as Glucose)	Δ C–N	Narrowing the C–N Ratio by A–F: 4 Populations G: 3 Populations	Concomitant Degradation of Volatile Solids in % (as Glucose)
A	0.565	78.75	2.50	23.5 → 13.6	43
B	0.502	90.00	3.21	25.7 → 12.8	50
C	0.439	101.25	4.13	28.5 → 11.9	58
D	0.376	112.50	5.36	32.1 → 10.7	67
E	0.313	123.75	7.07	37.3 → 9.0	76
F	0.251	135.00	9.64	45.0 → 6.4	86
G	0.188	146.25	13.93	57.8 → 16.1	72

Tab. 5. Calculation of the Decrease of the C–N Ratio of the Nutrient Supply by the Growth of One Bacterial Population at a 75% Carbon Turnover Rate and $Y_s = 0.502$ (see Eq. 1 in Tab. 3)

Start	$(C_6H_{12}O_6)_4 + 0.8\ NH_3$	C–N = 288 $(11.2)^{-1}$ = 25.71
Growth	$(C_6H_{12}O_6)_1 + 0.8\ NH_3 + 2\ O_2 \rightarrow 0.8\ [C_5H_7O_2N] + 2\ CO_2 + 4.4\ H_2O$	
Lysis/turnover	$0.8\ [C_5H_7O_2N] + 1\ O_2 + 1.4\ H_2O \rightarrow 0.5$ glucose $+ 0.8\ NH_3 + 1\ CO_2$	
Balance	$(C_6H_{12}O_6)_4 + 0.8\ NH_3 + 3\ O_2 \rightarrow (C_6H_{12}O_6)_{3.5} + 0.8\ NH_3 + 3\ CO_2 + 3\ H_2O$	
Rest for next population	$(C_6H_{12}O_6)_{3.5} + 0.8\ NH_3$	C–N = 252 $(11.2)^{-1}$ = 22.5

Δ M glucose = 4 – 3.5 = 0.5 = 90 g "volatile solids"; Δ C–N = 3.21.

three populations ($Y_s = 0.52$) diminish the C–N ratio from 32.1–12.8, degrading concomitantly 60% of the volatile solids.

Since the carbon–nitrogen ratio of the various types of the waste material deviates from the ratio considered optimum, they have to be mixed to arrive at a value which is required to lead – at least theoretically – to the fixation of the nitrogen in new biomass and in humic substances, or as ammonium adsorbed by inorganic and organic particles. Otherwise, nitrogen in excess will be lost as NH_3 to the air. If, on the other hand, nitrogen is deficient, the compost when applied as fertilizer will lead to the so-called nitrogen depression well known to farmers, i.e., soil nitrogen instead of being available for plant growth will be used for the further degradation of surplus carbon and thereby temporarily incorporated into microbial biomass.

4.2 Water Availability

General experience shows that organic matter can be stored without any risk of deterioration if kept dry, e.g., containing less than about 12% of moisture. In fact, drying is the most ancient method to preserve foodstuffs and animal feed. Less thorough drying (or inadvertent wetting) leads to instantaneous growth of microorganisms inherent in any organic matter (if not intentionally sterilized). Thus, water is certainly the initiator of microbial development on dead organic matter.

The water–microbe relationships in a compost pile are manifold. One would expect that there is an optimum moisture content on a mere weight basis, but this is not the case. This is because water exists in different states which are unequally available to microbes: water films covering the solid particles, capillary water, and matrix water. The various materials to be composted differ widely in their water holding capacity; i.e., the same moisture content in % of dry matter can result in a very different water availability. Thus, some materials require for optimum composting a water content of 75–90% (saw dust, straw), whereas others (grass clippings, food remains) need only a water content of 50–60%. Therefore, two other criteria are more suitable to characterize the water status:

(1) the *water activity*, expressed by the so-called a_w value (a_w: vapor pressure of water in a solution/vapor pressure of pure water.
(2) the *water potential* Ψ (more exactly "potential energy of water") which is related to the a_w value by Eq. (10) (Temple, 1981):

$$\Psi = RT\ V_w^{-1} \cdot \ln a_w \quad \text{(dimension kg m}^{-2}\text{)} \qquad (10)$$

V_w: partial molal volume of water.

Water activity is always less than 1.0, and water potential is always negative in real systems, since they express the availability of water in the real system contrasted to the availability of pure water under the same conditions.

The use of *water activity* to characterize the water status of a system has now been widely replaced by the measurements of the *water potential*, as outlined by Papendick and Mulla (1986). This is, because water activity is much too insensitive in systems with a high amount of readily available water; instead, the water

potential is regarded as the only approach for investigating water limitations caused by dryness, as discussed in detail by MILLER (1989, 1991) and DIX and WEBSTER (1995, pp. 59–66). Water potential is made up of several components, i.e., osmotic, matric, pressure and gravimetric. In composting systems, the matrix water potential (as measured with a tensiometer and expressed as a negative pressure in units of pascals [Pa]) is the most important one; it determines the extent of filling of the capillaries with water: a potential of -20 to -50 kPa is regarded as optimal, whereas -5 kPa stand for a too wet matrix, and -100 kPa for a too dry matrix. At -300 kPa pores of just ≤ 1 µm are water saturated, and $-1{,}380$ kPa correspond to the wilting point of vascular plants; this latter value is equivalent to a water activity of 0.990.

Apart from being essential for microbial growth, the moisture content of the starting material influences the course of the composting process: Too high a content hinders aeration and thus reduces the supply of oxygen for aerobic microbial growth, thereby favoring the establishment of anaerobic niches with the consequence of anaerobic metabolism leading to the formation of acid fermentation products. Even more important, however, is the fact that a high water content delays the self-heating because of the relatively high heat capacity of water. On the other hand, too little water, which of course can be easily corrected, retards the composting process.

The water content of the starting material is only one aspect of water and composting. In fact, the dynamics of water changes within a compost pile are rather complex. First, water is produced by aerobic microbial metabolism, about 0.45 kg of water per 1.0 kg of decomposed organic material. MILLER (1991) collected five values from the literature which are somewhat higher: WILEY and PEARCE (1957): 0.63 g H_2O g^{-1} garbage decomposed; GRIFFIN (1977): 0.55 g H_2O g^{-1} cellulose, HAUG (1979): 0.72 g H_2O g^{-1} sewage sludge; HOGAN et al. (1989): 0.5–0.53 g H_2O g^{-1} rice hulls + rice flour; HARPER et al. (1992) 0.5–0.6 g H_2O g^{-1} straw and poultry manure. (Although this is not of great influence in composting, this effect has to be considered when storing foods and feeds just at the threshold of the moisture requirements of microbial growth.) – Second, water is continually removed from the compost by the air supplied to meet the oxygen demand of the microorganisms and to remove heat from the compost pile to avoid temperatures above 60–70 °C. This withdrawal of water, which is actually desirable, must, of course, not proceed faster than the composting process, i.e., before the material is "stabilized"; otherwise, water has to be added for optimum completion of the process. At any rate, the water content of the compost pile decreases during the process, let's say from 50–70% to about 30%. This leads to a reduction of the microbial acitivities in general, but to an encouragement of microbes adapted to rather dry conditions, e.g., xerophilic fungi (DIX and WEBSTER, 1995, pp. 332–340).

4.3 Structure, Oxygen Supply and Aeration

The aerobic decomposition of organic matter requires oxygen in a definite stoichiometric relation. According to an equation, which will be used in Sect. 9.1, Tab. 15 for balancing the process, about 80 g of oxygen are used up for the degradation of 100 g of organic matter. It can be easily imagined that this amount is not initially contained in the compost pile and that it hardly reaches its interior just by passive diffusion. Thus, a very active aeration is necessary for an effective composting process. However, aeration has to fulfill another purpose which, as it turns out, is quantitatively of even greater importance: In a well isolated compost pile, the temperature can soon reach 80 °C and even higher. This is not compatible with microbial life, thus leading to *microbial suicide* (FINSTEIN, 1989). This heat has to be removed by ventilative cooling. As will be shown in Sect. 9.2 about 5 times as much air are needed for the removal of the heat as for the supply of the oxygen necessary for microbial metabolism.

Before further discussing aeration, another aspect has to be dealt with, i.e., the structure of the compost pile. This topic has been studied extensively by SCHUCHARDT (1977): The compost pile is a 3-phasic system comprising solid

matter, water and gas. For optimum performance of the process, the *free air space* should amount to 20–30% of the total volume. Since, in the course of composting, this value tends to decrease, it has to be kept that way by a repeated turning over of the pile. By this means also larger air channels, which are often built-up, are destroyed. The relationship between *pore volume* (water and gas volume) and *volume of solid matter* does not describe the system completely because the variance of particle size, of diameters of air channels, and of capillaries penetrating the individual particles finally determine the provision of the microbial population with oxygen. Oxygen reaches the microbial cells by a succession of various mechanisms: convection and diffusion within the free air space, and dissolution in the liquid phase. Even if thoroughly aerated, it appears that anaerobic microniches are left, allowing anaerobic microbial metabolism; thus, in practice composting appears to be not an entirely aerobic process (DERIKX et al., 1989; ATKINSON et al., 1996). This can be deduced from the formation of organic acids, leading to a drop of pH (especially during the first phase), and the appearance of traces of gases from anaerobic metabolism in the exhaust air, e.g., methane and N_2O (denitrification) (HELLMANN et al., 1997; LEINEMANN, 1998).

The amount of air to be supplied to a compost pile, usually measured in m^3 air kg^{-1} dry organic matter h^{-1}, is certainly a matter of practical experience. Of course, the uptake of oxygen by microbial metabolism can now be analyzed on-line, giving information about the degradative activity; alternatively, and possibly more conveniently, the CO_2 content of the exhaust air can be determined. According to Strom et al. (1980) the O_2 content of the exhaust air should not drop below 5%, and BIDLINGMAIER (1983) regards 10% as tolerable. DE BERTOLDI et al. (1983) recommend even 18% O_2, whereas SUHLER and FINSTEIN (1977) found no difference in composting efficiency between 10 and 18% O_2 in the exhaust air.

Aeration based on oxygen consumption has been one of the possible strategies for controlling the composting process, i.e., the Beltsville process. This approach, however, has been strongly opposed by FINSTEIN et al. (1986), who convincingly showed that aeration is quantitatively more important for regulating the temperature of the compost pile by *ventilative cooling* (Rutgers strategy) than for supplying oxygen to the microbes (see also Sect. 9.2). Since much more air is necessary to meet this requirement, any considerations regarding the amount of oxygen needed for the decomposition of organic matter are secondary. In addition, only part of the organic matter is degraded during a certain stage (and this is not known in advance, unless O_2–CO_2 analysis of the exhaust air is carried out on-line). Therefore, the oxygen requirement to be met cannot be calculated exactly to arrive at an optimum aeration. The wide variation of organic waste in its composition and, thus, in its degradability adds further uncertainty. And finally, since the efficiency of the air supply to carry out its tasks depends also on the structure of the waste material, the wide range of values for "optimum" composting to be found in the literature is not surprising. Of course, the engineer planning a composting plant must have some guidance to calculate the aeration devices, but these calculations can hardly be based on pure microbiological or thermodynamical data.

4.4 Temperature

Since production of heat and its preservation within the compost pile – at least for a certain period of time – is an outstanding characteristic of the composting ecosystem as compared with other terrestrial habitats, the parameter *temperature* has found the special interest of compost microbiologists and composting practitioners. The temperature relationship of microorganisms are dealt with in numerous treatises (e.g., INGRAHAM, 1962; SCHLEGEL and JANNASCH, 1992) and monographs (e.g., DIX and WEBSTER, 1995, pp. 53–54, pp. 322–332). Elementary information on this subject can be found in any textbook of general microbiology (e.g., LAMANNA and MALLETTE, 1959, pp. 422–444). Thus, there is no need here for a further discussion of this topic.