ELSEVIER

Journal of Biotechnology 95 (2002) 109–131

JOURNAL OF Biotechnology

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# The endoxylanases from family 11: computer analysis of protein sequences reveals important structural and phylogenetic relationships

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Received 5 June 2001; received in revised form 5 November 2001; accepted 20 December 2001

**Abstract**

Eighty-two amino acid sequences of the catalytic domains of mature endoxylanases belonging to family 11 have been aligned using the programs MATCHBOX and CLUSTAL. The sequences range in length from 175 to 233 residues. The two glutamates acting as catalytic residues are conserved in all sequences. A very good correlation is found between the presence (at position 100) of an asparagine in the so-called 'alkaline' xylanases, or an aspartic acid in those with a more acidic pH optimum. Four boxes defining segments of highest similarity were detected; they correspond to regions of defined secondary structure: B5, B6, B8 and the carboxyl end of the alpha helix, respectively. Cysteine residues are not common in these sequences (0.7% of all residues), and disulfide bridges are not important in explaining the stability of several thermophilic xylanases. The alignment allows the classification of the enzymes in groups according to sequence similarity. Fungal and bacterial enzymes were found to form mostly separate clusters of higher similarity. © 2002 Elsevier Science B.V. All rights reserved.

*Keywords:* Family 11 endoxylanases; Factor analysis classification; Sequence alignment; Structural relationships

## 1. Introduction

Xylan, a heteroglycan, is the main constituent of plant hemicelluloses. It is composed of a linear chain of xylose residues linked by $\beta(1\rightarrow4)$ glycosidic bonds, with a variety of substituents, depending on its source (Joseleau et al., 1992). Biodegradation of xylan is accomplished by a complex set of enzymes generically called 'xy-

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0168-1656/02/$ - see front matter 
PII: S0168-1656(02)00002-0

lanases', which are produced by fungi and bacteria (Biely, 1985).

The hydrolysis of the xylan backbone is performed mainly by the action of the endoxylanases (E.C. 3.2.1.8), which liberate xylooligosaccharides of different length (Biely, 1985). A large number of endoxylanases have been described, purified, characterized and sequenced from different microorganisms (Sunna and Antranikian, 1997), and based on sequence similarities and hydrophobic cluster analysis, they have been grouped in families 10 (or F) and 11 (or G) of the glycosyl hydrolases (Gilkes et al., 1991; Henrissat and Davies, 1997). Family 10 xylanases have a catalytic domain with molecular weights in the range of 32–39 K. The structure of the catalytic domain of several family 10 xylanases has been determined by X-ray crystallography and it consists of an eightfold β/α barrel (Harris et al., 1996). These enzymes show a greater catalytic versatility than family 11 endoxylanases (Biely et al., 1997). Family 11 xylanases, on the other hand, have a much smaller catalytic domain (around 20 kDa), with an all β-strand sandwich fold structure (Himmel et al., 1997). Some enzymes of family 10 and family 11 possess, in addition, cellulose or xylan binding domains (Törrönen and Rouvinen, 1997).

The endoxylanases have been found to be useful for several different biotechnological applications (Section 3.4). Therefore, for the design and protein engineering of endoxylanases, a good knowledge of their sequence and structure is of great importance.

For this purpose, a comparative analysis of the sequences of 82 catalytic domains of family 11 glycanases has been performed in this work. The large number of sequences available allows a fine analysis of sequence similarities, with the purpose of establishing structural relationships, determine location of conserved (and possibly essential) sequences and establish phylogenetic relationships.

## 2. Materials and methods

Sequences were obtained from the literature and from the public databases (SwissProt, GenBank and CAZy (http://afmb.cnrs-mrs.fr/~pedro/CAZY/ghf.html)). The 82 sequences were aligned by the method described below.

To define conserved residues in a reliable alignment of numerous sequences of very different length and of poor similarity is not trivial (de Fays et al., 1999). Although alignments are widely used, the rate of false positive functional similarities deduced from skewed aligned positions is not easily overcome (Briffeuil et al., 1998). In this study, an original methodology has been applied to obtain reliable alignments allowing a precise delineation of the corresponding relevant residues in the different sequences, despite the fact that some sequences share a very low percentage of identity (10%).

The first step of this methodology is based on the local alignment method MATCHBOX (Depiereux and Feytmans, 1992). Default parameters were used to delineate conserved boxes (defining Predicted Structural Conserved Regions, PSCR) with an estimated level of confidence (from 1 to 9) at each position of the alignment (Depiereux et al., 1997). In this work, PSCR's are defined for reliability scores below 5 on more than 2 non-redundant sequences, which corresponds to a rate of confidence of over 90%. This ensures less than 10% of 'false positive' aligned positions, a remarkable rate at this level of low similarity.

The second step of the procedure is based on the global alignment method CLUSTAL (Higgins et al., 1992). It is used to align the regions inserted between the anchor points defined above. Thus, the final alignment obtained by this original procedure takes advantage of both approaches: MATCHBOX for definition of the boxes (PSCR's), and CLUSTAL for the multiple alignment of the segments outside the boxes.

The proposed classification of the family 11 endoxylanases is based on a principal coordinates analysis computed from a similarity matrix between the sequences (Depiereux and Feytmans, 1991). The method takes advantage of a grouping of the sequences independent of any alignment steps and thus avoids a misclassification due to misalignments. Briefly, the similarity coefficient is based on matches, for a given threshold, between short unaligned segments of the sequences compared; eigenvectors and eigenvalues are computed

by matrix diagonalization, and sequences are plotted for factors 2 and 3, factor 1 being poorly discriminant. Eigenvector coordinates have been submitted to a cluster analysis, Ward's method, run on STATISTICA 4.1 (Statsoft, Inc) and plotted in an EXCEL spreadsheet.

PSCR delineation and factor analysis have been performed by the programs Align and Explore on the MATCHBOX server http://www.fundp.ac.be/sciences/biologie/bms/matchbox_submit.shtml and global alignment on the Clustal server http://dot.imgen.bcm.tmc.edu:9331/multi-align/Options/clustalw.html.

## 3. Results and discussion

Table 1 lists the 82 enzymes used in this study. It includes 36 sequences from bacteria, 43 from fungi, 2 from protozoa and 1 from insects. Twenty-two bacterial and 8 fungal enzymes are multidomain proteins; they correspond mainly to anaerobic microorganisms. Only the sequence of the catalytic domain of the mature enzymes is considered in this analysis. The amino terminus of the mature enzymes was taken to be either the experimentally determined terminus, when reported in the literature, or the predicted terminus, determined by means of the program SIGNALP (Nielsen et al., 1997). The enzymes from *Fibrobacter succinogenes*, *Neocallimastix frontalis* and *Neocallimastix patriciarum* have two family 11 catalytic domains each; these domains are considered separately in the analysis. The size of the catalytic domain of the multidomain enzymes is somewhat arbitrary; in Fig. 1 the sequences belonging to these enzymes are marked with a star at the beginning and/or end to indicate this fact.

The enzymes analyzed (not considering the multidomain proteins) range in molecular mass from 19 035 (*Trichoderma reesei*) to 25 908 (*Clostridium acetobutylicum*), and in sequence length from 175 (*Polypastron multivesiculatum* Xyn A) to 233 amino acid residues (*C. acetobutylicum*). A shorter sequence (Xyn 4 from *Aspergillus niger*; 153 residues, accession number U39785) was not included in this study because it aligned poorly to the other sequences due to its shorter length, although it is considered part of family 11 by CAZy.

Table 2 shows the pI's, pH and T° optima of those enzymes from the above list which have been purified and characterized. The pI values given are values measured in the laboratory; no theoretical estimations have been included. A wide range of pI values has been found: from a low of 3.5 for *Aspergillus kawachii* and *Aspergillus nidulans* to a high of $>10.25$ for *Streptomyces lividans* xylanases. Bacterial enzymes show pH optima ranging from 5.5 to 7, while those from fungi show a much wider range (from pH 2.0 to 8.0), the majority having acidic pH optima.

The three-dimensional structure of family 11 endoxylanases has been determined for several enzymes, from both bacteria and fungi (Table 3). The catalytic domain folds into two β sheets (A and B) constituted mostly by antiparallel β strands and one short alpha helix and resembles a partially closed right hand (Törrönen and Rouvinen, 1997). The loop between strands B7 and B8 forms the 'thumb' and the loop linking strands B6 and B9 is the 'cord'. A great similarity is found in all these structures. Fig. 2 presents a topology diagram showing the sequence of the secondary structure elements found in these enzymes. Two glutamic acid residues have been found to be catalytically essential and are located in strands B4 and B6, respectively (Törrönen and Rouvinen, 1997).

### 3.1. Multiple sequence alignment

The original alignment methodology used in this work is aimed at delineating structural features shared by all the xylanase sequences included in the analysis. First, boxes obtained from the MATCHBOX alignment program have been shown to accurately outline conserved structural motifs (De Bolle et al., 1995; Vinals et al., 1995; Bertrand et al., 1997, 1998; Depiereux et al., 1997). The fact that these predicted structurally conserved regions actually reflect robust structural similarities among the endoxylanases has been checked by comparison of the three-dimensional structures of the 11 xylanases of known crystallographic structure (Table 3) using the HOMOLOGY

Table 1
Family 11 xylanases used in this study

| Organism | Protein | Gene | Accession No. (GenBank) | Catalytic domain | | References |
|---|---|---|---|---|---|---|
| | | | | Length[a] | MW | |
| Bacteria | | | | | | |
| *Aeromonas caviae* | Xylanase I | *xynA* | D32065 | 183 | 20 212 | Kubata et al. (1997) |
| *Bacillus agaradhaerens* | Xylanase | | A48223 | 221 | 24 681 | Sabini et al. (1999) |
| *Bacillus circulans* | XLNA | *xlnA* | X07723 | 185 | 20 382 | Yang et al. (1988) |
| *Bacillus pumilus* | XYNA | *xynA* | X00660 | 201 | 22 515 | Fukusaki et al. (1984) |
| *Bacillus* sp. | Xylanase Y[b] | *xynY* | S51779 | 200 | 22 201 | Yu et al. (1993) |
| *Bacillus* sp. | Xylanase S | *xynS* | X59058 | 185 | 20 364 | Yu et al. (1993) |
| *Bacillus* sp. | Xylanase | *xynA* | U51675 | 185 | 20 220 | Jeong et al. (1998) |
| *Bacillus* sp. D3 | Xylanase | *xyn* | | 182 | 20 683 | Harris et al. (1997) |
| *Bacillus* sp. 41 M-1 | Xylanase J[b] | *xynJ* | AB029319 | 199 | 22 098 | Nakai et al. (1994) |
| *Bacillus stearothermophilus* | XYNA | *xynA* | U15985 | 191 | 21 083 | Cho and Choi (1995) |
| *Bacillus subtilis* | Xylanase A | *xynA* | M36648 | 185 | 21 451 | Paice et al. (1986) |
| *Caldicellulosiruptor* sp. Rt69B.1 | Xylanase[b] | *xynD* | AF036925 | 199 | 22 158 | Morris et al. (1999) |
| *Cellulomonas fimi* | XYLD[b] | *xynD* | X76729 | 198 | 21 451 | Millward-Sadler et al. (1994) |
| *Cellvibrio mixtus* | XYLA[b] | *xynA* | Z48925 | 207 | 22 550 | Millward-Sadler et al. (1995) |
| *Clostridium acetobutylicum* | Xylanase B | *xynB* | M31726 | 233 | 25 908 | Zappe et al. (1990) |
| *Clostridium stercorarium* | XynA[b] | *xynA* | D13325 | 193 | 22 130 | Sakka et al. (1993) |
| *Clostridium thermocellum* | Xylanase U[b] | *xynU* | AF047761 | 204 | 22 842 | Unpublished |
| *Clostridium thermocellum* | Xylanase V[b] | *xynV* | AF047761 | 204 | 22 787 | Unpublished |
| *Clostridium thermocellum* | XynA[b] | *xynA* | AB010958 | 200 | 22 445 | Hayashi et al. (1999) |
| *Clostridium thermocellum* | XynB[b] | *xynB* | AB010958 | 200 | 22 365 | Hayashi et al. (1999) |
| *Dictyoglomus thermophilum* | Xylanase B[b] | *xynB* | U76545 | 198 | 22 204 | Morris et al. (1998) |
| *Fibrobacter succinogenes* | XynC (domA)[b] | *xynC* | U01037 | 234 | 25 530 | Paradis et al. (1993) |
| *Fibrobacter succinogenes* | XynC (domB)[b] | *xynC* | U01037 | 216 | 24 437 | Paradis et al. (1993) |
| *Pseudomonas fluorescens* | XYLE[b] | *xynE* | Z48927 | 202 | 22 130 | Millward-Sadler et al. (1995) |
| *Ruminococcus albus* | XynA[b] | *xynA* | U43089 | 236 | 26 314 | Unpublished |
| *Ruminococcus flavefaciens* | XYLA[b] | *xynA* | Z11127 | 221 | 24 346 | Zhang and Flint (1992) |
| *Ruminococcus flavefaciens* | XynB[b] | *xynB* | Z35226 | 216 | 24 216 | Zhang et al. (1994) |
| *Ruminococcus flavefaciens* | XYLD[b] | *xynD* | S61204 | 213 | 24 031 | Flint et al. (1993) |
| *Ruminococcus* sp. | Xylanase 1[b] | *xyn1* | Z49970 | 213 | 23 904 | Unpublished |
| *Streptomyces lividans* | XlnB[b] | *xlnB* | M64552 | 192 | 21 064 | Shareck et al. (1991) |
| *Streptomyces lividans* | XlnC | *xlnC* | M64553 | 191 | 20 715 | Shareck et al. (1991) |
| *Streptomyces* sp. EC3 | Xylanase | *xln* | X81045 | 191 | 20 931 | Mazy-Servais et al. (1996) |
| *Streptomyces* sp. S38 | Xylanase | *xyl1* | X985518 | 190 | 20 585 | Georis et al. (1999) |
| *Streptomyces* sp. 36a | Xylanase | | | 192 | 20 973 | Nagashima et al. (1989) |
| *Streptomyces thermoviolaceus* | STX-II[b] | *stx*-II | D85897 | 190 | 20 738 | Tsujibo et al. (1997) |
| *Thermomonospora fusca* | TfxA[b] | *xynA* | U01242 | 190 | 20 900 | Irwin et al. (1994) |
| Fungi | | | | | | |
| *Ascochyta pisi* | Xylanase | *xyl1* | Z68891 | 208 | 22 185 | Lübeck et al. (1997) |
| *Aspergillus awamori* | EXLA | *exlA* | X78115 | 184 | 19 876 | Hessing et al. (1994) |

Table 1 (*Continued*)

| Organism | Protein | Gene | Accession No. (GenBank) | Catalytic domain | | References |
|---|---|---|---|---|---|---|
| | | | | Length[a] | MW | |
| *Aspergillus kawachii* | Xylanase B | *xynB* | P48824[c] | 207 | 22 259 | Unpublished |
| *Aspergillus kawachii* | XynC | *xynC* | D14848 | 184 | 19 876 | Ito et al. (1992a) |
| *Aspergillus nidulans* | X22 | *xlnA* | Z49892 | 188 | 20 235 | Perez-González et al. (1996) |
| *Aspergillus nidulans* | X24 | *xlnB* | Z49893 | 188 | 20 077 | Perez-González et al. (1996) |
| *Aspergillus niger* | Xylanase A | *xylA* | A19535 | 184 | 19 890 | Maat et al. (1992) |
| *Aspergillus niger* | XynNB | *xynNB* | D38071 | 188 | 20 069 | Kinoshita et al. (1995) |
| *Aspergillus niger* | Xyn5 | *XYN5* | U39784 | 195 | 21 143 | Unpublished |
| *Aspergillus oryzae* | XynG1 | *xynG1* | AB003085 | 189 | 20 589 | Kimura et al. (1998) |
| *Aspergillus tubigensis* | XYLA | *xlnA* | L26988 | 184 | 19 837 | de Graaff et al. (1994) |
| *Aspergillus tubigensis* | Xylanase B | | A39368 | 207 | 22 240 | Patent WO 9414965-A (1994) |
| *Aureobasidium pullulans* | XynA | *xynA* | U10298 | 187 | 20 074 | Li and Ljungdahl (1994) |
| *Chaetomium gracile* | CgXA | *cgxA* | D49850 | 189 | 20 149 | Yoshino et al. (1995) |
| *Chaetomium gracile* | CgXB | *cgxB* | D49851 | 211 | 22 525 | Yoshino et al. (1995) |
| *Claviceps purpurea* | Xylanase | *xyl1* | Y16969 | 197 | 21 460 | Giesbert et al. (1998) |
| *Cochliobolus carbonum* | Xyl1 | *XYL1* | L13596 | 191 | 20 856 | Apel et al. (1993) |
| *Cochliobolus carbonum* | Xyl2 | *XYL2* | U58915 | 191 | 21 199 | Apel-Birkhold and Walton (1996) |
| *Cochliobolus carbonum* | Xyl3 | *XYL3* | U58916 | 183 | 19 858 | Apel-Birkhold and Walton (1996) |
| *Cochliobolus sativus* | Xylanase | *xyl2* | AJ004802 | 212 | 23 658 | Emami and Hack (2001) |
| *Cryptococcus* sp. S-2 | Xyn-CS2 | *xyn-CS2* | D63382 | 184 | 20 209 | Iefuji et al. (1996) |
| *Humicola insolens* | Xyl1 | *xyl1* | X76047 | 208 | 23 814 | Dalboge and Heldt-Hansen (1994) |
| *Magnaporthe grisea* | XYN22 | *xyn22* | L37529 | 194 | 21 427 | Wu et al. (1995) |
| *Neocallimastix frontalis* | Xylanase 2 | *XYN2* | S48865 | 212 | 23 933 | Unpublished |
| *Neocallimastix frontalis* | XYN3 (domA)[b] | *xyn3* | X82266 | 223 | 24 394 | Durand et al. (1996) |
| *Neocallimastix frontalis* | XYN3 (domB)[b] | *xyn3* | X82266 | 223 | 24 532 | Durand et al. (1996) |
| *Neocallimastix patriciarum* | XYLA dom1)[b] | *xynA* | X65526 | 226 | 24 941 | Gilbert et al. (1992) |
| *Neocallimastix patriciarum* | XYLA (dom2)[b] | *xynA* | X65526 | 225 | 24 770 | Gilbert et al. (1992) |
| *Orpinomyces* strain PC-2 | XynA[b] | *xynA* | U57819 | 225 | 24 810 | Li et al. (1997) |
| *Paecilomyces varioti* | PVX | | P81536[c] | 194 | 21 365 | Kumar et al. (2000) |
| *Penicillium* sp. 40 | XynA | *xynA* | AB035540 | 190 | 20 713 | Kimura et al. (2000) |
| *Penicillium purpurogenum* | XynB | *xynB* | Z50050 | 183 | 19 371 | Díaz et al. (1997) |
| *Pichia stipitis* | Xylanase A[b] | *xynA* | AF151379 | 232 | 26 291 | Unpublished |
| *Piromyces* sp. (inactive) | XYLA[b] | *xynA* | X91858 | 234 | 25 558 | Fanutti et al. (1995) |
| *Piromyces* sp. (active) | XYLA[b] | *xynA* | X91858 | 222 | 24 803 | Fanutti et al. (1995) |
| *Schizophyllum commune* | Xylanase A | *xynA* | P35809[c] | 197 | 20 965 | Oku et al. (1993) |
| *Thermomyces lanuginosus* | XynA | *xynA* | U35436 | 206 | 22 614 | Schlacher et al. (1996) |
| *Trichoderma harzianum* E58 | 20 kD Xylanase | | P48793[c] | 190 | 20 690 | Yaguchi et al. (1992b) |
| *Trichoderma reesei* | XYNI | *xyn1* | X69574 | 178 | 19 035 | Törrönen et al. (1992) |
| *Trichoderma reesei* | XYNII | *xyn2* | X69573 | 190 | 20 829 | Törrönen et al. (1992) |
| *Trichoderma reesei* | Xyn2 | *XYN2* | U24191 | 190 | 20 731 | La Grange et al. (1996) |
| *Trichoderma viride* | Xylanase IIA | | A44594 | 190 | 20 759 | Yaguchi et al. (1992a) |
| *Trichoderma viride* | Xylanase IIB | | A44595 | 190 | 20 743 | Unpublished |
| Protozoa | | | | | | |
| *Polyplastron multivesiculatum* | XYN A | *xynA* | AJ009828 | 219 | 25 192 | Unpublished |
| *Polyplastron multivesiculatum* | Xylanase | *polyX* | AB011274 | 175 | 19 394 | Unpublished |
| Insect | | | | | | |
| *Phaedon cochleariae* | Xylanase | | Y17908 | 200 | 22 070 | Unpublished |

[a] Number of amino acid residues.
[b] Multidomain protein.
[c] SWISS-PROT entry.

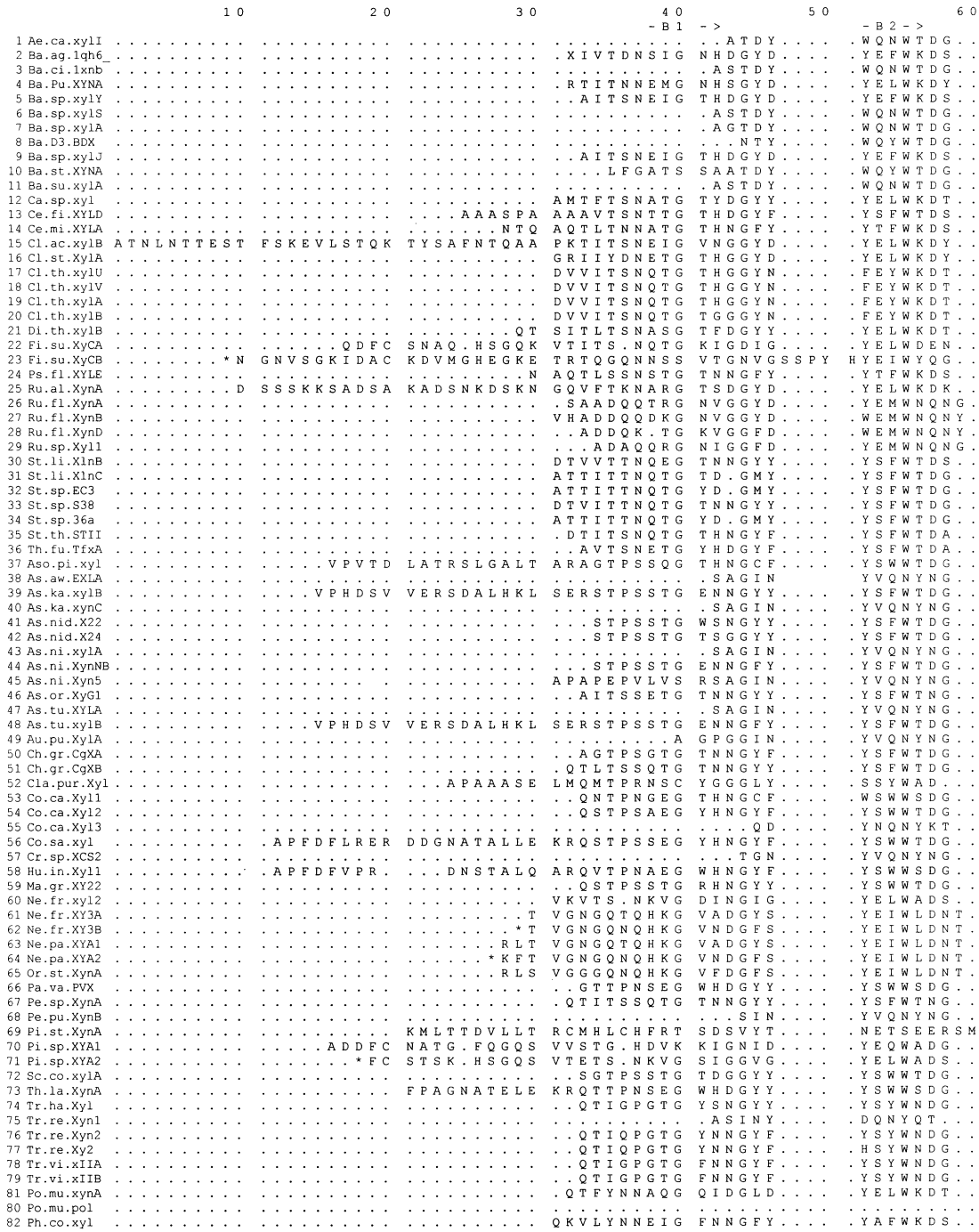

Fig. 1. Multiple alignment of 82 sequences of family 11 endoxylanases performed by MATCHTAL. The sequences follow the same order given in Table 1. On top of the alignment, secondary structure elements observed in the crystal structures are provided. Boxes (Predicted Structural Conserved Regions) obtained by MATCHBOX are shaded. The two catalytic Glu residues (E169 and E289 according to the numbering of the multiple alignment) are in boldface. Residue 100 (N or D, depending on the pH optimum, see text) is underlined. The putative start and/or end of the catalytic domain sequences belonging to multiple domain xylanases is indicated by a star. For abbreviations see Table 1.

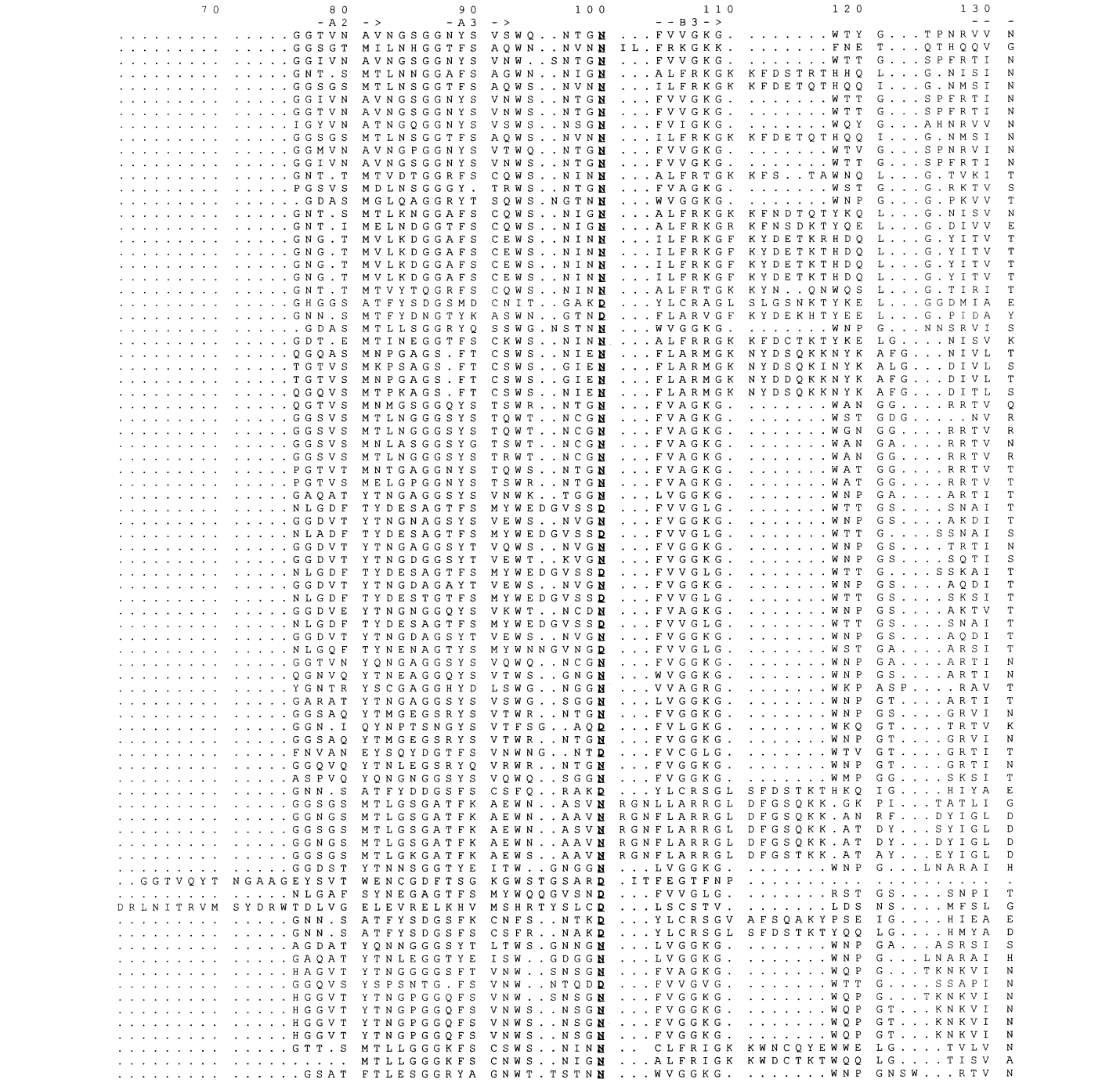

Fig. 1. (*Continued*)

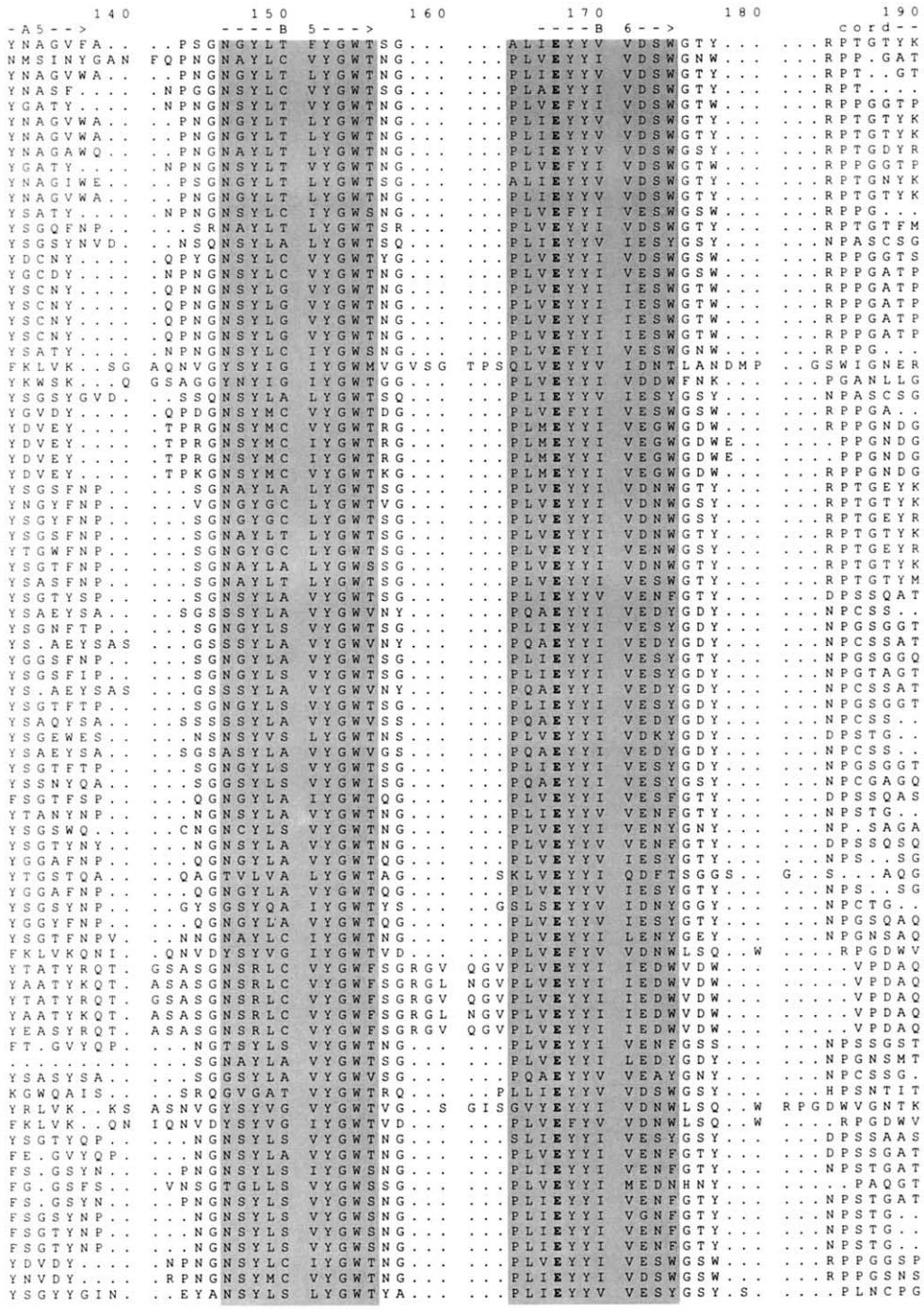

Fig. 1. (*Continued*)

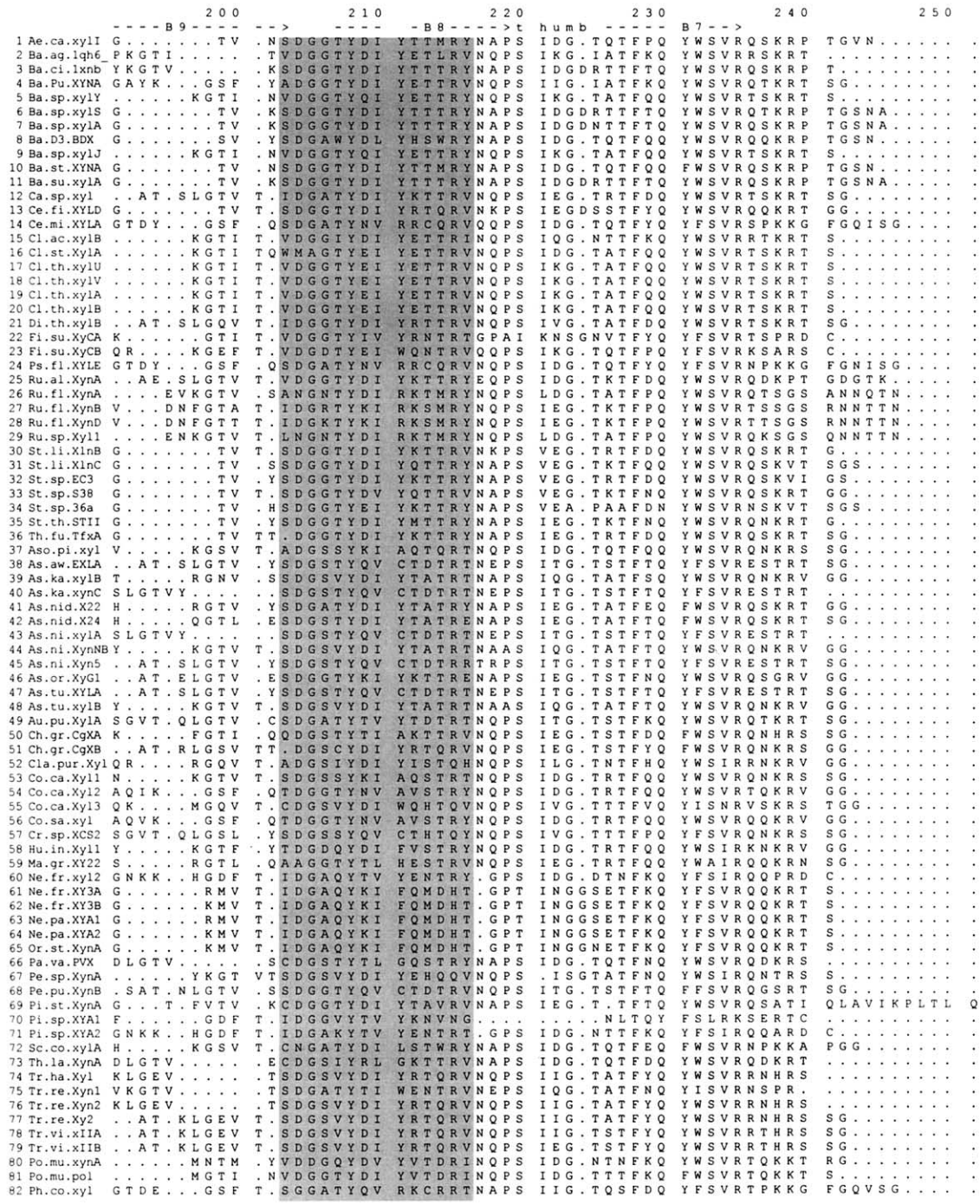

Fig. 1. (*Continued*)

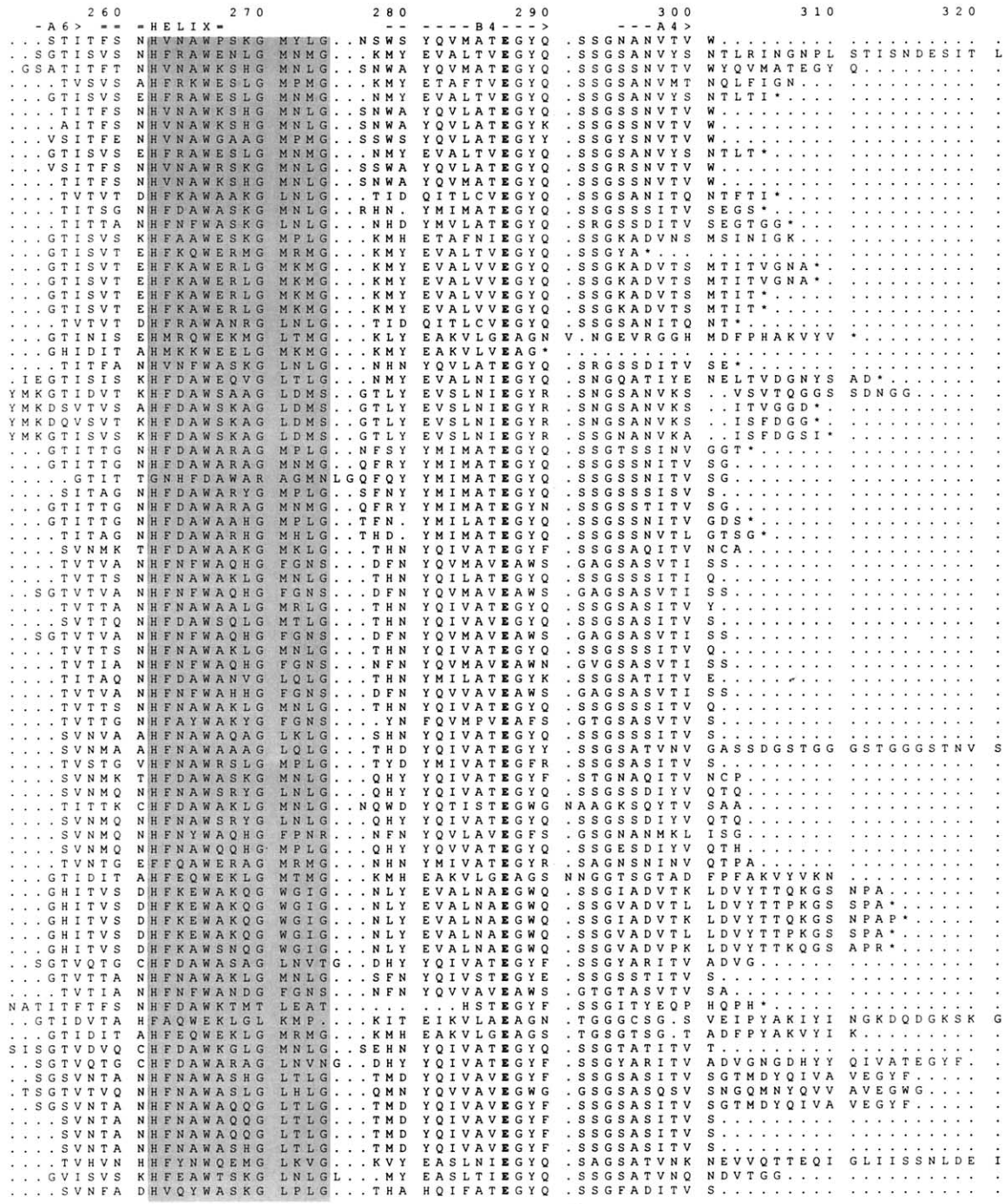

Fig. 1. (*Continued*)

Table 2
Isoelectric point, pH and T° optimum of family 11 xylanases of known sequence

| Organism | Xylanase | pI | pH optimum | Optimum T° | Reference |
|---|---|---|---|---|---|
| Bacteria | | | | | |
| *Aeromonas caviae* | Xylanase I | 7.1 | 7.0 | 55 | Kubata et al. (1992) |
| *Bacillus agradhaerens* | xyl 11 | 8.8 | n.d. | n.d. | Sabini et al. (1999) |
| *Bacillus pumilus* | XYNA | n.d. | 6.5 | 45–60 | Panbangred et al. (1983) |
| *Bacillus* sp. D3 | Xylanase | 7.7 | 6.0 | 75 | Harris et al. (1997) |
| *Bacillus* sp. 41 M1 | Xylanase J | 5.5 | 9.0 | 50 | Nakamura et al. (1992) |
| *Bacillus subtilis* | Xylanase A | 8.9 | n.d | n.d. | Paice et al. (1986) |
| *Caldicellulosiruptor* sp. Rt69B.1 | Xylanase | n.d. | 5.5 | 70 | Morris et al. (1999) |
| *Clostridium acetobutylicum* | Xylanase B | 8.5 | 5.5–6 | 60 | Lee et al. (1987) |
| *Clostridium stercorarium* | XynA | 4.5 | 7.0 | 75 | Sakka et al. (1994) |
| *Clostridium thermocellum* | XynA | n.d. | 6.5 | 65 | Hayashi et al. (1999) |
| *Dictroglomus thermophilum* | Xylanase B | n.d | 6.5 | 85 | Morris et al. (1998) |
| *Fibrobacter succinogenes* | XynC | 6.2 | 6.5 | n.d. | Paradis et al. (1993) |
| *Ruminococcus flavefaciens* | XYLA | 5.0 | 5.5 | 50 | Flint et al. (1991)<br>García-Campayo et al. (1993) |
| *Streptomyces lividans* | XlnB | 8.4 | 6.5 | 55 | Kluepfel et al. (1990) |
| *Streptomyces lividans* | XlnC | >10.25 | 6.0 | 57 | Kluepfel et al. (1992) |
| *Streptomyces* sp. EC3 | Xylanase | 9.1 | n.d. | n.d. | Mazy-Servais et al. (1996) |
| *Streptomyces* sp. S38 | Xyl1 | 9.8 | 6.0–6.5 | 55–60 | Georis et al. (2000) |
| *Streptomyces thermoviolaceus* | STX-II | 8.0 | 7.0 | 60 | Tsujibo et al. (1992) |
| *Thermomonospora fusca* | TfxA | 10 | 7.0 | n.d. | Irwin et al. (1994) |
| Fungi | | | | | |
| *Aspergillus awamori* | EXLA | 3.7 | n.d. | n.d. | Hessing et al. (1994) |
| *Aspergillus kawachii* | XynC | 3.5 | 2.0 | 50 | Ito et al. (1992) |
| *Aspergillus nidulans* | X22 | 6.4 | 5.5 | 62 | Fernández-Espinar et al. (1993) |
| *Aspergillus nidulans* | X24 | 3.5 | 5.5 | 52 | Fernández-Espinar et al. (1996) |
| *Aspergillus niger* | Xyl A (or I) | 3.7 | 3.0 | n.d. | Maat et al. (1992)<br>Krengel and Dijkstra (1996) |
| *Aspergillus niger* | XynNB | n.d. | 5.0 | n.d. | Kinoshita et al. (1995) |
| *Aspergillus tubigensis* | XYLA | 3.6 | n.d. | n.d. | de Graaff et al. (1994) |
| *Aureobasidium pullulans* | XynA (APX II) | 9.4 | 4.8 | 54 | Li et al. (1993) |
| *Cochliobolus carbonum* | Xyl1 | >9.3 | 4.0–8.0 | 45 | Holden and Walton (1992) |
| *Cochliobolus carbonum* | Xyl2 and 3 | >9.3 | 5.0 | n.d. | Holden and Walton (1992) |
| *Cryptococcus* sp. S-2 | Xyn-CS2 | 7.4 | 2.0 | 40 | Iefuji et al. (1996) |
| *Magnaporthe grisea* | XYN22 | 9.7 | n.d. | n.d. | Wu et al. (1995) |
| *Paecilomyces varioti* | PVX | 3.9 | 5.5–7.0 | 65 | Krishnamurthy and Vithayathil (1989) |
| *Penicillium* sp. 40 | XynA | 4.7 | 2.0 | 50 | Kimura et al. (2000) |
| *Penicillium purpurogenum* | XynB | 5.9 | 3.5 | 50 | Belancic et al. (1995) |
| *Schizophyllum commune* | Xylanase A | 4.5 | 5.0 | 50 | Jurasek and Paice (1988) |
| *Thermomyces lanuginosus* | XynA | 4.1 | 6.5 | 65 | Gomes et al. (1993)<br>Schlacher et al. (1996) |
| *Trichoderma harzianum* E58 | 20 kD xylanase | 9.4 | 5.0 | 50 | Wong and Saddler (1992) |
| *Trichoderma reesei* | XYNI | 5.2 | 3.5–4 | n.d. | Törrönen et al. (1992) |
| *Trichoderma reesei* | XYNII | 9.0 | 4.5–5.5 | n.d. | Törrönen et al. (1992) |
| *Trichoderma viride* | Xylanase IIA | 9.3 | 5.0 | 53 | Wong and Saddler (1992) |

n.d.: not determined.

Table 3
Family 11 endoxylanases of known three-dimensional structure

| Organism | Protein | PDB code | References |
|---|---|---|---|
| Bacteria | | | |
| *Bacillus agaradhaerens* | Xylanase | 1qh6 | Sabini et al. (1999) |
| *Bacillus circulans* | XLNA | 1xnb | Wakarchuk et al. (1994a) |
| *Bacillus* sp. D3 | Xylanase[a] | | Harris et al. (1997) |
| *Dictyoglomus thermophilum* | XynB[a] | 1fsj | McCarthy et al. (2000) |
| Fungi | | | |
| *Aspergillus kawachii* | XynC | 1bk1 | Fushinobu et al. (1998) |
| *Aspergillus niger* | XylI or A | 1ukr | Krengel and Dijkstra (1996) |
| *Paecilomyces varioti* | Xylanase[a] | 1pvx | Kumar et al. (2000) |
| *Thermomyces lanuginosus* | XynA[a] | 1yna | Gruber et al. (1998) |
| *Trichoderma harzianum* E58 | Xylanase | 1xnd | Campbell et al. (1993) |
| *Trichoderma reesei* | XYNI | 1xyn | Törrönen and Rouvinen (1995) |
| *Trichoderma reesei* | XYNII | 1xyp | Törrönen et al. (1994) |

[a] Thermophilic protein.

package (MSI, San Diego) or the FSSP program (Holm and Sander, 1996). In addition, the use of CLUSTAL to globally align the regions inserted between these anchor points allows to highlight several key residues in less conserved regions. In short, the alignment obtained on the basis of sequence similarity also reflects structural similarities among the endoxylanases.

The alignment is shown in Fig. 1. The residues are numbered on top; the numbering exceeds the length of any individual sequence since it includes all gaps assigned by the alignment. The secondary structure elements are numbered as shown in Fig. 2.

Four boxes (shaded in Fig. 1) are found along the whole set of 82 sequences and correspond to the PSCRs. Interestingly, the sequence alignment provides a pattern of aligned segments and gaps consistent with the observed secondary structure elements. Indeed, the lowest sequence homology is found in the regions between beta strands (residues 94–103 between A3 and B3; residues 111–130 between B3 and A5; residues 238–254 between B7 and A6). The region corresponding to the thumb, (between strands B7 and B8) is, however, very well conserved along all the sequences, except for *Piromyces* sp. XYLA. This last enzyme is reported to be the inactive form of the protein, in contrast to *Piromyces* sp. XYLB, the active form, that also contains the conserved segment defining the thumb region. The cord region (between B6 and B9) is also conserved. The PSCR's, in particular, correspond to secondary structure elements: box 1 to B5, box 2 to B6, box 3 to B8 and box 4 to the helix.

The amino terminal regions of the aligned sequences show no similarities in the first 30 or so residues. One sequence is particularly long in this region (*C. acetobutylicum*). One of the sequences (*P. multivesiculatum*, AB011274) starts only at residue 81, and lacks strands B1, B2 and part of A2, suggesting that B1 and B2 may not be necessary for enzymatic activity. Residue 40 is a G in 60 sequences, and is missing in 15. It belongs to B1 in the structure of *T. reesei* XYN II (Törrönen et al., 1994). Its importance is unclear, since B1 is missing totally or in part in the indicated 15 sequences.

The segment corresponding to B2 shows good similarity among the sequences. Position 52 is in most cases an aromatic residue: 63 sequences have a Y, while 14 show a W or a F. At position 55, W predominates (70 sequences), while 62 sequences have a D in position 57. Between B2 and A2, two long insertions (probably forming a loop) are found in the endoxylanases from *Penicillium* sp. and *Pichia stipitis*. 50 G's are observed in position 76 and 50 in position 77. Strand A2 shows low similarity except at position 81, where 24 Y and

35 M are found. In the loop linking A2 and A3, 61 G's are observed in position 86 and 67 in position 87, but not necessarily together in the same sequence. In A3, a highly conserved F or Y (79 sequences) is found in position 89 and 75 W in 93; in this last case, the few replacements are F or Y; only one non-conserved replacement (H) is observed in *P. stipitis*.

Residue 100 is in all cases a D (27) or N (65); as we will see below, this residue is related to the pH optimum of the enzyme. At the end of B3, G109 is present in 79 sequences (it is replaced by a K in *Bacillus agaradhaerens*) and allows a special twist to the chain (Törrönen and Rouvinen, 1997).

A5 is not present in *P. stipitis*, which shows a big gap between 110 and 144; in this sequence, B3 and B5 are probably linked by a short loop. B5 corresponds to the first box detected by MATCHBOX, indicating a highly conserved stretch of the sequence, particularly YGW (152–154), present in all 82 enzymes. Y152 is strongly hydrogen bonded to E167; it seems to be of great functional importance since its mutation to F (in *Bacillus circulans* XLNA) leads to a totally inactive enzyme (Wakarchuk et al., 1994a). At position 150 21 Cys are present, the highest number found at a particular location in all the sequences (see below).

The next box corresponds to B6. It is preceded by a highly conserved Pro at 164 (present in 74 sequences) and Leu 165 (74 sequences). E167 is common to all sequences and corresponds to one of the catalytic residues (the nucleophile); it is followed by two highly conserved Y's (75 in position 168, replaced in the rest of the enzymes by F;

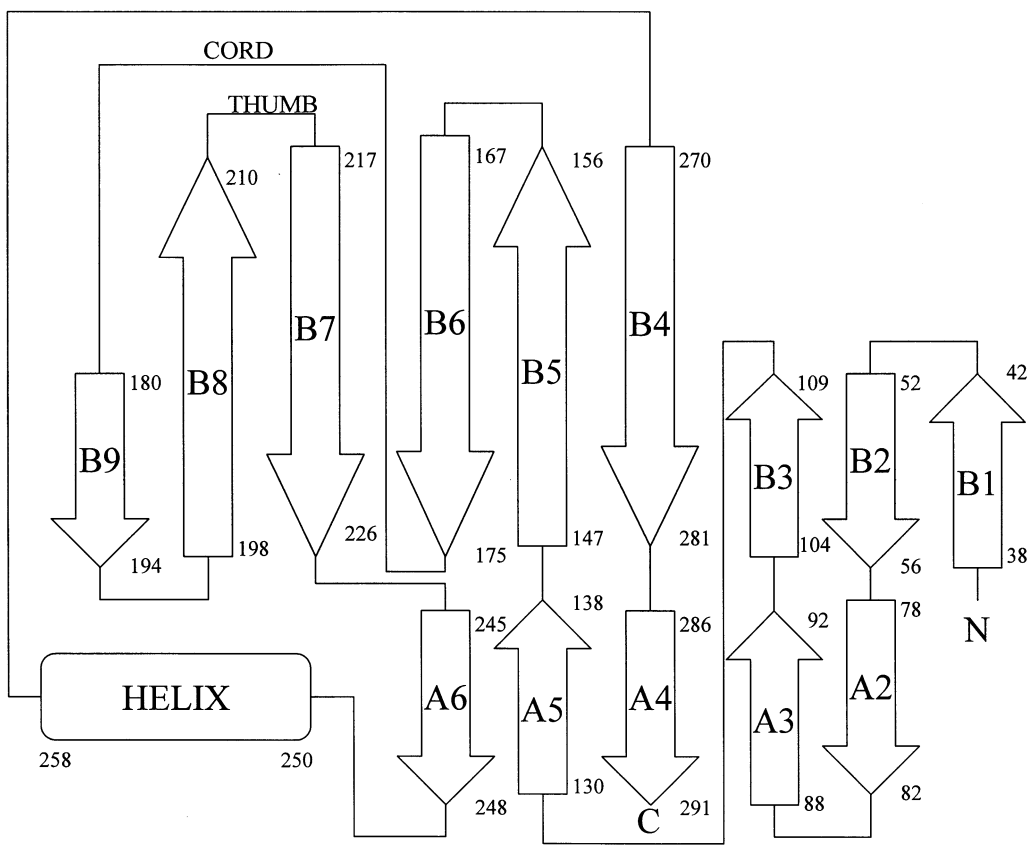


Fig. 2. Topology diagram of the family 11 endoxylanases. The residue numbering refers to that of Fig. 1. The figure is adapted from Törrönen et al. (1994).

and common to all in 169) and by two aliphatic hydrophobic residues in positions 170 and 171. Tyr 169 links both catalytic glutamates, acting as a charge stabilizing residue (Törrönen and Rouvinen, 1997), and its mutation to F in XLNA of *B. circulans* leads to a large decrease in activity (Wakarchuk et al., 1994a).

The 'cord' shows low similarity, except for a Pro (found in 70 sequences and missing in 7) in position 185. B9 is a stretch of very low similarity and varies considerably in length, but it is followed by the third high similarity box, corresponding mainly to B8. Between B9 and B8, two highly conserved residues are apparent: D204 (in 76 sequences) and G205 (in 80 sequences); this last residue is considered important in hairpin formation (Törrönen and Rouvinen, 1997). Y208 is present in all 82 sequences, R215 in 72 and N217 in 69 (this last residue is missing in 8 sequences).

The 'thumb' is well conserved; it has a consensus sequence PSIXG where X is almost any residue and the others show few and mainly homologous replacements. Pro 219 gives a twist to the strand at the beginning of the thumb. B7 is also well conserved; residue 227 is a T in 77 sequences and 228 is F in 81 cases; a consensus sequence QYWSVR can be proposed for residues 230–235 (R is replaced by K in one instance and the other residues show mainly conservative replacements).

The loop connecting B7 and A6 differs in length; the longest being in the enzyme from *P. stipitis*, which also shows the longest loop between B2 and A2. No significant similarities are apparent in A6, which is immediately followed by the helix.

The last box of high similarity comprises the carboxyl end of the α-helix and the following 6–7 residues. H262 is present in 79 sequences, W263 in 80 and G270 in 79.

B4 does not show high similarities, except for E287 (boldface in Fig. 1), a residue present in all sequences, which corresponds to the acid-base glutamate participating in catalysis, and which is followed by a highly conserved G (70 sequences). The last well defined secondary structure is A4. A highly conserved consensus sequence SSGS precedes and starts this strand.

The carboxyl terminus of the sequences is highly variable in length. The longest is found in *B. agaradhaerens* and *P. multivesiculatum*, stretching 25 and 22 residues, respectively, beyond the end of A4.

### 3.2. Acidophily and thermostability

A number of family 11 endoxylanases have been reported to be acidophilic. It has been postulated that for xylanases that function optimally under acidic conditions, residues spatially adjacent to the acid/base catalytic glutamate influence the pH optimum (Törrönen and Rouvinen, 1995). In particular, the substitution of N100 (underlined in Fig. 1) by D shifts the pH optimum from 5.7 to 4.6, as has been demonstrated by mutational, kinetic, and structural studies of N100D in *B. circulans* XYLA (Joshi et al., 2000). This agrees with the mutational analysis of xylanase C of *A. kawachii*, in which the single substitution of Asp 100 to Asn at this key position dramatically elevates its pH optimum from 2 to 5 (Fushinobu et al., 1998). Structural studies of xylanase A (or I) from *A. niger* led to a similar conclusion. In the crystal structure of this enzyme of low pH optimum (Krengel and Dijkstra, 1996), Asp 100 is assigned a critical role.

An examination of the enzymes of known sequence for which the pH optimum has been determined (Table 2), shows that this correlation holds true with only one exception. The enzymes showing a pH optimum below 5 have D at position 100, while N is present in those with pH optima of 5 or more. The exception is XynC from *F. succinogenes*, an anaerobic bacterium from the rumen. This enzyme shows a pH optimum of 6.5 but has a D at position 100. This enzyme has two catalytic domains, and the pH optimum reported in Table 2 corresponds to the native enzyme; the separate domains have a pH optimum of 6.0 (Zhu et al., 1994).

In conclusion, there is a strong correlation in that the residue hydrogen bonded to the general acid/base catalyst at position 100 is asparagine in the so-called 'alkaline' xylanases, whereas it is aspartic acid in those with a more acidic pH optimum.

Thermostability is an important issue in the properties of endoxylanases, due to their biotechnological applications, particularly in cellulose biobleaching. Of the enzymes listed in Table 2,

seven of bacterial origin (*Bacillus* D3, *Caldicellulosiruptor* sp., *Clostridium stercorarium*, *Clostridium thermocellum*, *Dictyoglomus thermophilum*, *Streptomyces thermoviolaceus* and *Thermomonospora fusca*) and two from fungi (*Paecilomyces varioti* and *Thermomyces lanuginosus*) are considered thermophilic, based on their optimal temperature and stability at high temperature. Table 3 shows that the three-dimensional structure of four of these enzymes has been determined.

Thermophilicity and thermostability may be explained by a variety of factors and structural parameters (Kumar et al., 2000). Of those, the importance of S–S bridges and aromatic 'sticky patches' can be analyzed by sequence alignment. Additional structural features potentially involved in thermal stability, such as salt bridges, aromatic interactions and entropic effects have been postulated in family 11 xylanases (Georis et al., 2000).

Cysteine residues are not very common in these enzymes. Of the total number of residues in the 82 sequences listed in Table 1, only 117 are Cys, a 0.7%. Twenty-seven of the sequences have no Cys and 14 have only one; therefore, at least half of the total possesses no disulfide bridges. The three-dimensional structure shows that an S–S bridge is found in xylanase A from *A. niger* connecting Cys 186 to Cys 211, thus attaching the cord to the large beta-sheet (B8) (Krengel and Dijkstra, 1996). These two half-cystine residues are conserved in a few other fungal family 11 xylanases (*A. kawachii*, *Aspergillus awamori*, *A. niger* Xyn5, *Aspergillus tubigensis*, *Cryptococcus* sp. and *Penicillium purpurogenum*). The xylanases from the bacteria *Cellvibrio mixtus* and *Pseudomonas fluorescens* and of the insect *Phaedon cochleariae* have Cys at positions 188 and 213, which may be forming a similar bridge. The presence of this disulfide bridge may influence the stability of these proteins, although it does not give (at least to the enzymes analyzed so far) a thermophilic character.

Of the seven thermophilic xylanases listed, three have no cysteines, and the three-dimensional structure of the *Dictyoglomus thermophilus* enzyme shows no S–S bonds, although its sequence has 3 Cys. On the other hand, *T. lanuginosus* and *P. varioti* xylanases, both thermophilic, do have an S–S bridge linking Cys 203 (located in B9) and Cys 261 (in the $\alpha$ helix). *Cochliobolus carbonum* Xyl3 and *Schizophyllum commune* XylA also possess only two Cys and in the same positions; the T° optimum of the former has not been reported, while the latter has a value of only 50 °C (Table 2). All these results suggest that S–S bridges are unlikely to be of importance in the thermophilicity of family 11 xylanases.

As pointed out by Turunen et al. (2001), thermophilicity (activity at high temperature) and thermostability do not necessarily depend on the same structural factors. They introduced a disulfide bridge plus other minor mutations in *T. reesei* XynII (C203-C261) significantly increasing the thermostability without affecting the temperature optimum. Wakarchuk et al. (1994b) have introduced an S–S bridge at the same position in *B. circulans* xylanase, obtaining similar results. Thus, the introduction of S–S bridges to enzymes may affect both properties differently.

Harris et al. (1997) propose that the *Bacillus* D3 xylanase (lacking S–S bridges) is stabilized through 'sticky patches' between pairs of molecules through the interaction of surface aromatic residues. These residues are Tyr 53, 78, 120, 201, 290, 295 and Trp 207 and 214. When the alignment is analyzed, it shows that Tyr 78, 120 and Trp 207 are unique to this sequence (no aromatic residues are present in those positions in the remaining 81 sequences), while Trp 214 is shared by only 1 sequence (not thermophilic) and no other aromatic residues are found in this location. The remaining four residues show no clear alignment pattern. Therefore, it can be concluded that the 'sticky patch' pattern described for the *Bacillus* D3 xylanase is very unique, and it is unlikely to play an important role in stabilizing the other thermophilic family 11 xylanases of known sequence.

Shibuya et al. (2000) using random gene shuffling between a mesophilic (*S. lividans* XlnB) and a thermophilic (*T. fusca* TfxA) enzyme have shown the importance of the amino terminal segment of the protein in temperature stability. However, if the first 50 residues (our numbering) of the thermophilic enzymes in this study are aligned, no

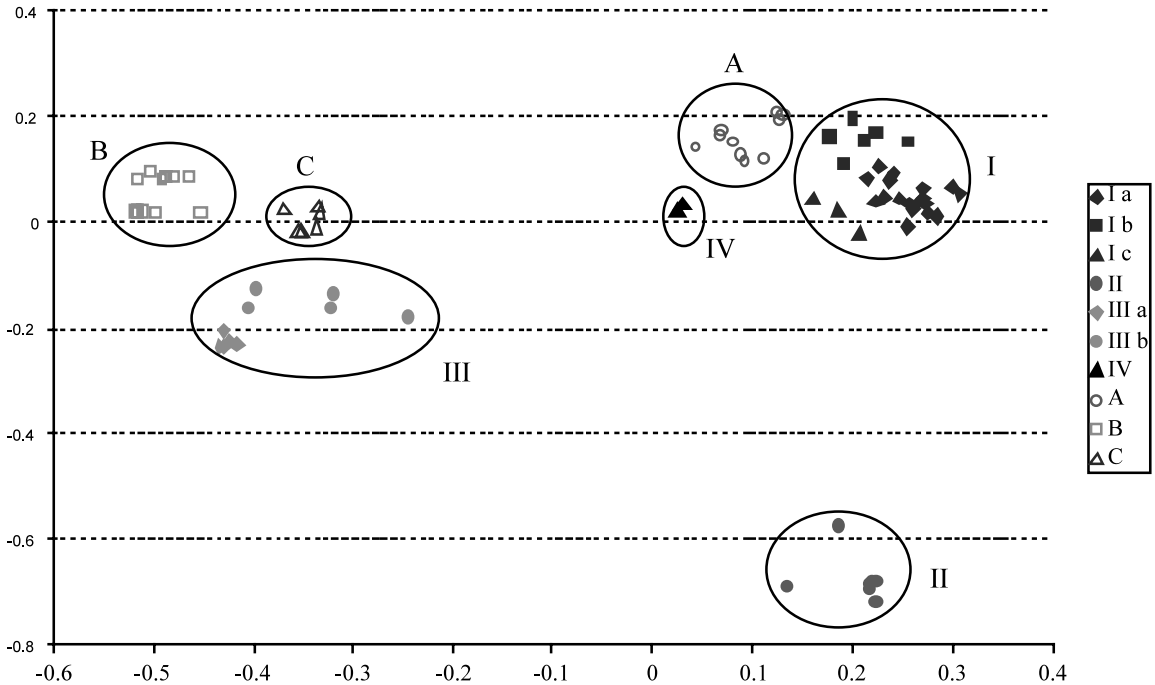


Fig. 3. Results from the factor analysis. Graphical representation of the sequences in the plane of factors 2 and 3. Each point corresponds to a sequence, the position on the plot being associated to a percentage of the total variability within the data set. Distances separating each position in the plot are directly related to the sequence homology. Groups containing mainly sequences of fungi (I, II, III, IV) are marked by filled symbols.

clear similarity pattern is observed, indicating that, again, the proposed thermostabilizing factor may be unique to the *T. fusca* enzyme.

### 3.3. Classification of the family 11 xylanases

A factor analysis (Explore subprogram of MATCHBOX) was performed in order to define groups and subgroups among the 82 sequences under study. Sequences have been represented in a three-dimensional space, each factor being associated to a percentage of the total variability between the sequences. The first factor is generally trivial, and the grouping of the sequences was performed in the plane of factors 2 and 3 (Depiereux and Feytmans, 1992). Graphical representation of the sequences in the plane of factors 2 and 3 (Fig. 3) was obtained directly from the program MATCHBOX and represented via Excel. The distances separating each position in the plot are directly related to the sequence homology, thus allowing a classification. Sequences close in the plane of factors 2 and 3 were grouped/clustered, leading to the classification presented in Table 4. A first clustering, based on the distance between coordinates in the plane of factors 2 and 3, led to the definition of a total of seven groups. Those groups were labeled (A, B, C, I, II, III, IV) *a posteriori*, on the basis of the origin (fungal or bacterial) of the sequences belonging to them. The two larger groups (I and III), were further divided into subgroups on the basis of the distance between coordinates in the plane of factors 2 and 3 within the group. Group B, although containing many sequences (13) was not divided into subgroups as the distribution of points is narrow (factor 2 comprised between $-0.453$ and $-0.518$; factor 3 comprised between 0.015 and 0.087) in comparison to the distribution of, for example, group III ($-0.431 <$ factor $2 < -0.240$; $-0.236 <$ factor $3 < -0.161$).

This method avoids affecting the sequence classification by misalignments occurring in a previous

step, and represents the sequences on a plane taking into account Euclidian distance rather than hierarchical merging. The graphical representation of the eigenvectors (sequence coordinates) in the plane of factors 2 and 3 (Fig. 3) allows to classify and group the sequences by eye, since the distances separating each position in the plot are directly related to differences in the sequences. The classification obtained has been validated by a clustering (Ward method) performed on the sequence coordinates.

Interestingly, the groups obtained from the factor analysis are highly homogeneous, meaning that they mostly contain only sequences from either bacteria or fungi. It is also noteworthy that some bacterial sequences are more homologous to sequences of fungal endoxylanases than to sequences of other bacteria (see for example group I).

In this work a robust classification methodology based on factor analysis, without previous sequence alignment and without reference to any phylogenetic inference is applied for the first time to classify a large set of sequences. Interestingly, the classification of xylanases presented in Table 4 compares favorably with previous classifications based on smaller sequence datasets. In particular, our results are in good agreement with the classification presented by Georis et al. (1999) deduced from a phylogenetic tree analysis on 63 sequences. According to their study, family 11 endoxylanases were subdivided into six main groups: three for

Table 4
Classification of family 11 xylanases based on a factor analysis

| | | | | | |
|---|---|---|---|---|---|
| Ia | Tr.re.XYNI | II | As.ni.XylA | *A* | *Ce.fi.XYLD* |
| Ia | Tr.re.XYNII | II | Pe.pu.XynB | *A* | *Th.fu.TfxA* |
| Ia | Tr.vi.xIIA | II | As.tu.XYLA | *A* | *St.sp.S38* |
| Ia | Tr.vi.xIIB | II | As.ni.Xyn5 | *A* | *St.th.STII* |
| Ia | Th.la.XynA | II | As.ka.XynC | *A* | *St.li.XlnC* |
| Ia | Pe.sp.XynA | II | As.aw.EXLA | *A* | *Ba.ci.1xnb* |
| Ia | Pa.va.1pvx | II | Au.pu.XylA | *A* | *St.sp.EC3* |
| Ia | Ch.gr.CgXB | | | *A* | *St.li.XlnB* |
| Ia | Aso.pi.xyl | IIIa | Ne.fr.XY3A | *A* | *Ba.su.xylA* |
| Ia | As.or.XyG1 | IIIa | Ne.fr.XY3B | *A* | *Ba.sp.xylA* |
| Ia | As.nid.X24 | IIIa | Ne.pa.XYA1 | | |
| Ia | As.ka.xylB | IIIa | Ne.pa.XYA2 | *C* | *Di.th.xylB* |
| Ia | Tr.ha.1xnd | IIIa | Orpin.XynA | *C* | *Ru.fl.XynB* |
| Ia | As.nid.X22 | | | *C* | *Ru.fl.XynD* |
| Ia | Ma.gr.XY22 | IIIb | Fi.su.XyCA | *C* | *Ca.sp.xyl* |
| Ia | Co.ca.Xyl1 | IIIb | Fi.su.XyCB | *C* | *Ru.sp.Xyl1* |
| Ia | Ch.gr.CgXA | IIIb | Pi.sp.XYA1 | *C* | *Ru.fl.XynA* |
| Ia | As.tu.xylB | IIIb | Pi.sp.XYA2 | | |
| Ia | As.ni.XynNB | IIIb | Ne.fr.xyl2 | *B* | *Ba.ag.1qh6* |
| | | | | *B* | *Ru.al.XynA* |
| Ib | Co.ca.Xyl2 | IV | Co.ca.Xyl3 | *B* | Po.mu.POX |
| Ib | Cla.pu.Xyl | IV | Pi.st.XynA | *B* | Po.mu.xylA |
| Ib | Co.sa.xyl | | | *B* | *Cl.ac.xylB* |
| Ib | Sc.co.xylA | | | *B* | *Ba.sp.xylJ* |
| Ib | Hu.in.Xyl1 | | | *B* | *Ba.sp.xylY* |
| Ib | Ba.D3.BDX | | | *B* | *Cl.th.xylV* |
| | | | | *B* | *Cl.st.XylA* |
| Ic | *Ce.mi*.XYLA | | | *B* | *Cl.th.xylA* |
| Ic | Ps.fl.XYLE | | | *B* | *Cl.th.xylB* |
| Ic | Ph.co.xyl | | | *B* | *Cl.th.xylU* |
| | | | | *B* | *Ba.pu.XYNA* |

Sequence of bacterial enzymes are in italics and enzymes produced by protozooa or insects are underlined. For abbreviations see Table 1 and Fig. 1.

fungi, two for Gram positive bacteria and one for Gram negative bacteria.

A similar subdivision is found here: groups I, II and III contain mainly fungal enzymes. The enzymes in groups I and II are mostly the 20 kDa enzymes from *Ascomyceta* and *Basidiomyceta*. Most enzymes of group I exhibit a basic pI. Those in group II show an acidic pI. Enzymes of group III are mainly produced by anaerobic fungi. Like in the classification proposed by Georis et al. (1999) two enzymes produced by *F. succinogenes* (XyCA and XyCB), an anaerobic Gram-negative bacterium, also fall in this group.

In addition to those three groups associated mainly to fungal enzymes, a fourth group that was not present in previous classifications emerges from the present factor analysis. It only contains two enzymes. One is produced by *C. carbonum* (Xyl3) and is clearly distinct from Xyl1 and Xyl2 produced by the same fungus. In the classification proposed by Georis et al. (1999), this enzyme is isolated in the unrooted phylogenetic tree. The second enzyme in group IV is produced by *P. stipitis* (XynA); this enzyme has not been included in any previous classification.

Bacterial enzymes are mainly divided into three groups (A, B, C). Group A contains mainly enzymes produced by members of the *Actinomycetaceae* and the *Bacillaceae* families, strictly aerobic Gram-positive bacteria. Groups B and C are more closely related and contain mainly enzymes from anaerobic Gram-positive bacteria, such as those from *Clostridium* or *Ruminococcus*, which usually live in the rumen. Two bacterial enzymes, XylE and XylA xylanases from *P. fluorescens* and *C. mixtus*, respectively, strictly aerobic Gram-negative bacteria, are found in subgroup Ic. In terms of sequence similarities, those two Gram-negative bacterial enzymes more closely resemble xylanases produced by fungi (group I) than other Gram-positive bacterial enzymes (e.g. groups A, B, C). They were also classified in a distinct group by Georis et al. (1999).

### 3.4. Biotechnological significance

Xylanases are finding an increasing number of applications, both alone and in combination with other enzymes. Among them are cellulose pulp biobleaching (Buchert et al., 1994), bread-making (Courtin et al., 1999) and saccharification of lignocellulosic biomass (Lee, 1997). These applications require enzymes capable of operating under specific and often unnatural conditions. Parameters of particular interest are thermostability and pH optimum. Biobleaching, for instance, requires thermostable and alkali-stable enzymes. Family 11 xylanases may be of particular interest in biobleaching due to their smaller size; a fact which may facilitate penetration in the cellulose fiber network.

Optimizing enzyme properties for a particular application can be achieved by random and site-directed mutagenesis. Arase et al. (1993) have achieved a significant stabilization of *Bacillus pumilus* XynA by random mutagenesis. Four heat-resistant mutants were isolated, and the stabilizing mutations were found to be clustered in the N-terminal region. In three of the four mutants, a mutation of G92 to S or to D was observed. Residue 92 is located in the A3 strand, and it is always a polar or charged residue except in *B. pumilus* and *Penicillium* sp. where it is a G (Fig. 1); the introduction of an S or a D at that position may allow the formation of a stabilizing hydrogen bond.

An example of the use of site-directed mutagenesis is given by Turunen et al. (2001). They have introduced a disulfide bridge by means of the mutations S203C–N261C, thus increasing significantly the half-life of the enzyme at 65°. As shown in Fig. 1, the thermophilic xylanase from *T. lanuginosus* possesses this bridge.

It has proved difficult to manipulate the properties of an enzyme in a predictable manner (Törrönen and Rouvinen, 1997). However, for the design and protein engineering of endoxylanases with properties suitable for their different applications, a good knowledge of its sequence and structure is a necessary condition. The information and analysis presented in this publication should be useful for this purpose.

## Acknowledgements

This work was financed in part by grants from DIPUC (Dirección de Investigación y Postgrado,

Pontificia Universidad Católica de Chile) and FONDECYT grants 1960241, 3950015 and 8990004 (Líneas Complementarias).

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