Revisiting the Phenomenon of Cellulase Action: Not All Endo- and Exo-Cellulase Interactions Are Synergistic

Mariska Thoresen 1, Samkelo Malgas 1,2, Mpho Stephen Mafa 1,3 and Brett Ivan Pletschke 1,*

1 Enzyme Science Programme (ESP), Department of Biochemistry and Microbiology, Rhodes University, Makhanda (Grahamstown) 6140, South Africa; g09t0934@campus.ru.ac.za (M.T.); samkolo.malgas@up.ac.za (S.M.); mafams@ufs.ac.za (M.S.M.)
2 Department of Biochemistry, Genetics and Microbiology, University of Pretoria, Hatfield 0028, South Africa
3 Department of Plant Sciences, University of the Free State, P.O. Box 339, Bloemfontein 9300, South Africa
* Correspondence: b.pletschke@ru.ac.za; Tel.: +27-46-6038081

Abstract: The conventional endo–exo synergism model has extensively been supported in literature, which is based on the perception that endoglucanases (EGs) expose or create accessible sites on the cellulose chain to facilitate the action of processive cellobiohydrolases (CBHs). However, there is a lack of information on why some bacterial and fungal CBHs and EGs do not exhibit synergism. Therefore, the present study evaluated and compared the synergistic relationships between cellulases from different microbial sources and provided insights into how different GH families govern synergism. The results showed that CmixA2 (a mixture of TlCel7A and CtCel5A) displayed the highest effect with BaCel5A (degree of synergy for reducing sugars and glucose of 1.47 and 1.41, respectively) in a protein mass ratio of 75–25%. No synergism was detected between CmixB1/B2 (as well as CmixC1/C2) and any of the EGs, and the combinations did not improve the overall cellulose hydrolysis. These findings further support the hypothesis that “not all endo-to exo-cellulase interactions are synergistic”, and that the extent of synergism is dependent on the composition of cellulase systems from various sources and their compatibility in the cellulase cocktail. This method of screening for maximal compatibility between exo- and endo-cellulases constitutes a critical step towards the design of improved synergistic cellulose-degrading cocktails for industrial-scale biomass degradation.

Keywords: cellulose; endo-glucanase; enzymatic hydrolysis; exo-glucanase; glycoside hydrolase; synergy

1. Introduction

In nature, microorganisms have evolved diverse degradative strategies involving an arsenal of enzymatic machinery to assist them in cellulose de-polymerization [1,2]. Cellulases belong to a large family of glycosyl hydrolases (GH), which display the ability to cleave β-1,4 glycosidic bonds in cellulose chains via an acid hydrolysis mechanism [1,3]. Based on their amino acid sequence and 3D structural similarities, the catalytic machinery of known cellulases has been classified into different glycoside hydrolase (GH) families: 1, 3, 5, 6, 7, 8, 9, 12, 26, 44, 45, 48, 51 and 74 as documented in the Carbohydrate-Active enZYmes database (CAZy; http://www.cazy.org). Different GH families have been shown to have low sequence similarities with one another; thus, they display a variety of topologies [2,4]. These differences, predominantly in the shape of the active-site pockets, determine the endo- or exo-mode of action of a given enzyme [2,4]. Although cellulases are traditionally viewed as having either exo- or endo-acting activities, recent evidence supports the idea that many enzymes have evolved activities against a broad range of substrates, due to conformational changes in their active sites [5,6].

Traditionally, a system of three main enzymatic activities has been reported to be indispensable for cellulose hydrolysis [7,8]. These include (i) cellubiohydrolases, CBHI/II
Catalysts 2021, 11, 170

(EC 3.2.1.91 and EC 3.2.1.176), which processively cleave cellobiose units from one end (reducing or nonreducing) of the cellulase chain; (ii) endoglucanases, EGs (EC 3.2.1.4), which cleave at random internal regions of the cellulose chain to produce new chain oligosaccharides, and (iii) β-glucosidases, βgls (EC 3.2.1.21), which primarily hydrolyze glycosidic bonds of cellobiose and cellodextrins [8–10]. Efficient enzymatic hydrolysis of cellulose can only be achieved by a complete and balanced composition of cellulases, which co-operate with each other to de-polymerize the substrate [11]. The model generally used to describe this type of collaboration is referred to as enzyme synergism [1,12,13]. Although intensive research on cellulose-degrading enzymes for biomass degradation has mostly focused on the glycoside hydrolases, other carbohydrate-active catalytic domains and proteins (nonhydrolytic), known as lytic polysaccharide mono-oxygenases (LPMOs), swollenins/expansins and CBMs have been shown to contribute to the overall degradation of cellulose by means of increasing cellulose accessibility [14,15]. However, for the purpose of this study, the focus will solely be on the interaction between glycosidases.

Synergy between cellulolytic enzymes has been documented previously, including, (i) exo–exo synergism, (ii) processive endo–endo synergism, (iii) endo–exo synergism, and (iv) intramolecular synergy between catalytic domains and cellulose binding domains (CBMs) [16–19]. Despite the numerous research efforts and various hypotheses made towards elucidating the synergism between cellulases on crystalline cellulose, the synergistic mechanisms by which cellulases hydrolyze cellulose are not yet fully comprehended [17,20]. Due to the overlapping functions and conflicting natures of endo- and exo-glucanases, the questions as to how these enzymes synergize at a molecular level, or why only a limited number of CBHs and EGs exhibit synergism, remain a mystery [21–23]. Moreover, only a few studies have investigated the synergistic relationships between fungal and bacterial enzymes, thus there is a lack of understanding on how the structural and mechanistic features of various GH families affect the synergistic relationship of a given cellulase cocktail for efficient cellulose hydrolysis. This raises questions, such as how do these enzymes function to depolymerize the diverse regions of the substrate, do all endo- and exo-acting enzymes act synergistically, and what are the factors that govern enzyme synergism? Furthermore, optimizing the composition of cellulase mixtures is an effective method to increase/improve their hydrolytic efficiency and reduce protein loadings during lignocellulose degradation.

The aim of this study was to provide insights into how the molecular mechanisms of cellulases from different GH families and various microbial sources govern synergism, by means of mapping various CBH to EG interactions. The enzymes used in this study included three CBHIs from *Hypocrea jecorina* (HjCel7A), *Clostridium stercorarium* (CsCel48A), and *Trichoderma longibrachiatum* (TlCel7A); two CBHIIs from a microbial source (Cel6A) and *Clostridium thermocellum* (CtCel5A); three EGs from *Bacillus amyloliquefaciens* (BaCel5A), *Thermotoga maritima* (TmCel5A), and *Trichoderma reesei* (TrCel7B); a cellulase mixture containing three endoglucanases (EglA (Cel9), EglB (Cel12), and EglC (Cel74)) from *Aspergillus niger* (AnEG); and a β-glucosidase from *Aspergillus niger* (Novozyme 188; βgl). This rational approach of screening for maximal compatibility between different GH families could ultimately provide a platform for a better understanding of the specific interactions between the enzymes of interest and how the complex synergistic activities of different enzymes assist one another in degrading cellulose. Consequently, this can shed light on designing synergistic enzyme cocktails, which are tailored to effectively convert biomass into fermentable sugars, thus reducing the overall cellulase loadings required to achieve efficient biomass conversion.

2. Results and Discussion

2.1. Enzyme Characterization and Substrate Specificity Studies

All the cellulases used in this study were characterized based on their physicochemical properties (temperature optima, pH optima, and thermal stability). The pH optima of the enzymes were in the range of 4.0–7.0, with variable temperature optima in the range of
40–60 °C and the enzymes displayed thermal stability between 37 and 50 °C for over 24 h (data not shown). The cellulases were also tested for their specific activities on different cellulosic substrates suspended in sodium citrate buffer (50 mM, pH 5.0) at 37 °C (Table 1).

Table 1. Specific activities of cellulolytic enzymes on various cellulosic substrates.

| Enzyme | Specific Activity (U/mg) | CMC | Avicel | pNPC | pNPG | Cellopentitol |
|--------|--------------------------|-----|--------|------|------|--------------|
|        |                          |     |        |      |      |              |
|        | Cellulbiohydrolase I (CBH I) |     |        |      |      |              |
| (HjCel7A) |                     | 0.35 ± 0.01 | 0.10 ± 0.00 | 0.25 ± 0.01 | 0.06 ± 0.01 | Nd |
| (TICel7A) |                     | 0.70 ± 0.02 | 0.35 ± 0.01 | 0.15 ± 0.00 | 0.03 ± 0.01 | Nd |
| (CsCel48A) |                   | 0.70 ± 0.02 | 0.028 ± 0.00 | 0.02 ± 0.00 | 0.09 ± 0.00 | Nd |
|        | Cellulbiohydrolase II (CBH II) |     |        |      |      |              |
| (CICel5A) |                     | 4.90 ± 0.20 | 0.026 ± 0.00 | 0.017 ± 0.00 | 0.08 ± 0.00 | 0.50 ± 0.02 |
| Microbial Cel6A |               | 0.08 ± 0.00 | 0.05 ± 0.00 | 0.023 ± 0.00 | 0.03 ± 0.00 | 0.48 ± 0.02 |
|        |                          |     |        |      |      |              |
|        | Endo-glucanase (EG) |     |        |      |      |              |
| (BaCel5A) |                     | 21.30 ± 0.80 | 0.062 ± 0.00 | 5.59 ± 0.20 | 0.15 ± 0.00 | 0.55 ± 0.02 |
| (TmCel5A) |                     | 22.01 ± 0.05 | Nd | 0.85 ± 0.03 | 0.20 ± 0.01 | 1.04 ± 0.05 |
| (TrCel7B) |                    | 20.16 ± 1.00 | 0.16 ± 0.00 | 2.02 ± 0.09 | 0.05 ± 0.00 | 1.39 ± 0.06 |
| AnEG (Cel 9, 12, 74) |       | 42.60 ± 0.80 | 0.41 ± 0.02 | 0.80 ± 0.03 | 4.90 ± 0.20 | 2.05 ± 0.10 |
|        |                          |     |        |      |      |              |
|        | Glucosidase |     |        |      |      |              |
| βgl | 0.30 ± 0.01 | Nd | 0.30 ± 0.01 | 53.2 ± 1.30 | Nd |

One U was defined as the amount of enzyme releasing 1 µmol of product per minute unless stated otherwise. Values are presented as means ± S.D. (n = 3). “Nd” = not detected.

In general, the CBHIs displayed the highest activities on Avicel, CMC, and pNPC, except for CsCel48A which displayed very low activities on Avicel and pNPC. All three CBHIs displayed low activities on pNPG and displayed no cellopentaitol activity. Previous studies also reported low or no activity of GH family 48 on crystalline cellulose [24–27]. Interestingly, CsCel48A displayed high CMCase activity (0.70 U/mg), indicating that it exhibited endo-activity. The catalytic domains of C. thermocellum (Cel48S) and C. cellulolyticum (Cel48F), which have 54–56% amino acid sequence identity to CsCel48A, have previously been solved and found to be structurally different from other processive cellulases [28,29]. It has been proposed that the flexible loops forming the tunnel of Cel48s start as an open α/β8-barrel structures, with an open active cleft topology [33–35]. Another noteworthy feature of many GH5 family proteins is that their protein sequences sometimes include additional modules with different functions (particularly CBMs) [36]. Depending on the location (N-or C-terminal), the CBM is appended on the catalytic domain of GH5 enzymes, this may confer the catalytic domains to target different substrates with different chemistry and structures [36].

Among the CBHIs, CtCel5A displayed the highest CMCase and cellopentaitol activity of 4.90 and 0.5 U/mg, respectively, whereas the microbial Cel6A displayed very low activity on CMC (0.08 U/mg), but higher cellopentaitol activity of 0.48 U/mg. Both CBHIs displayed exceptionally low activities on Avicel, pNPC, and pNPG [31,32]. Compared to Cel5A, Cel6A displayed minor endoglucanase (CMC) activity, which was probably due to differences in their active site tunnels. Studies have reported that GH5 enzymes may behave as endo-glucanolytic CBHs (multifunctional enzymes), which may be attributable to their typical (α/β)8-barrel structures, with an open active cleft topology [33–35]. Another noteworthy feature of many GH5 family proteins is that their protein sequences sometimes include additional modules with different functions (particularly CBMs) [36]. Depending on the location (N-or C-terminal), the CBM is appended on the catalytic domain of GH5 enzymes, this may confer the catalytic domains to target different substrates with different chemistry and structures [36].

Among the EGs assessed, AnEG displayed the highest CMCase, Avicelase, glucosidase, and cellopentaitol cleaving activities. BaCel5A displayed the highest activity on pNPC of 5.59 U/mg, whereas TmCel5A, TrCel7B, and AnEG exhibited 0.85, 2.02, and 0.80 U/mg activity on pNPC, respectively. BaCel5A, TmCel5A, and TrCel7B displayed similar CMCase activity at 21.3, 22.01, and 20.16 U/mg, respectively, and displayed little to no activity on Avicel. BaCel5A, TmCel5A, and TrCel7B displayed 0.15, 0.20, and 0.05 U/mg glucosidase
activity, respectively, and displayed 0.55, 1.04, and 1.39 U/mg cellopentaitol cleaving activity, respectively. The catalytic sites of EGs exhibit extended open substrate-binding clefts, offering an easier entry to the cellulose chain [37]. Thus, CMC is the preferred substrate for determining EG activity, since CMC contains carboxymethyl substituents that can only enter enzyme active sites with an open conformation [3,38,39]. These enzymes displayed higher Avicelase activity compared to the CBHI enzymes assessed (excluding TICel7A), as well as all the CBHIII enzymes assessed in this study, thus, suggesting that these EGs exhibit exo-glucanase activity on micro-crystalline cellulose [8]. In addition, Kim [40] reported that endoglucanases from a Bacillus sp. and various fungi, may exhibit Avicelase activity in addition to CMCase activity with the help of an exo-activity resident in the same molecule. Studies have revealed that EGs may exhibit processive behavior due to a CBM attached to the catalytic domain and have performed studies to support the critical role of CBMs for EG processivity [36,41]. Although the mode of processivity seems to be more common in CBHIs, studies have reported that EGs can change their character to facilitate a processive mode of action on recalcitrant substrates [36,41]. Their ability to cleave internal sites of the cellulose chain and to release soluble oligosaccharides prior to separating from the cellulose chain has resulted in the introduction of a subclass of cellulases, referred to as processive endo-cellulases [23,25,30].

Finally, βgl exhibited high glucosidase activity of 53.2 U/mg and minimal activity on CMC and pNPC. No detectable enzyme activity was observed on Avicel or cellopentaitol. The enzyme was, therefore, assumed to have exhibited true β-glucosidase-like catalytic properties.

2.2. Exo–Exo Synergy between CBHI (TICel7A) and CBHII (Microbial Cel6A/CtCel5A)

Exo–exo synergy between CBHI (TICel7A) and CBHII (microbial Cel6A) was investigated to determine the optimal CBH mixture (CBHI + CBHII) cocktail required for cellulose hydrolysis (Figure 1a). TICel7A was selected because it was the most active enzyme on Avicel (as seen in Table 1). A confirmatory study of the CBHI to CBHII synergistic ratio was performed by swapping CBHII (microbial Cel6A) with a CBHII from a different GH family and source (CtCel5A) (Figure 1b).

![Figure 1](image_url)

**Figure 1.** Synergistic degradation of Avicel by various ratios of TICel7A (CBHI) and microbial Cel6A (CBHII) (a) and TICel7A (CBHI) and CtCel5A (CBHII) (b). Assays were performed in sodium citrate buffer (0.05 M; pH 5.0) and incubated at 37 °C for 24 h. Values represented as mean values ± S.D. (n = 3).

This exo–exo synergism is a phenomenon that was first confirmed by Fägerstam and Pettersson in 1980 [42] and has since then been confirmed by other researchers [9,16,43,44]. According to the exo–exo synergy model, it has been hypothesized that CBHI and CBHII prefer to hydrolyze cello-oligosaccharides from opposing sides of the cellulose chain.
(CBHI—reducing and CBHII—nonreducing end). Consequently, this renders a strong synergistic relationship between the two different CBHs [28]. Based on these results, the ratio of 75% CBH I (TICel7A):25% CBHII (microbial Cel6A or CtCel5A) was selected as the benchmark (optimal ratio) CBH mix (Cmix) for subsequent experiments. This ratio agrees with the CBHI (70%):CBHIII (30%) ratio reported by previous researchers [9,44].

2.3. Synergism between Exo- and Endo-Glucanases

Cellulose hydrolysis and the synergistic interactions between various Cmix combinations (CmixA1, CmixA2, CmixB1, CmixB2, CmixC1, and CmixC2) and endo-glucanases were investigated (Table 2), whereby CmixA1 is (TICel7A + microbial Cel6A), CmixA2 is (TICel7A + CtCel5A), CmixB1 is (HjCel7A + microbial Cel6A), CmixB2 is (HjCel7A + CtCel5A), CmixC1 is (CsCel48A + microbial Cel6A), and CmixC2 is (CsCel48A + CtCel5A).

2.3.1. Synergy between CmixA1 (TICel7A and Microbial Cel6A) or CmixA2 (TICel7A and CtCel5A) and Various Endoglucanases

CmixA1 and BaCel5A displayed the highest degree of synergy (DS) at the ratio of 75%:25% followed by a ratio of 50%:50%. The total reducing sugars and glucose released from Avicel by this enzyme combination (75%:25%) were 1.13 mg/mL and 1.07 mg/mL, respectively. The highest DS around 1.40 also demonstrated that CmixA1 and BaCel5A were co-operating during hydrolysis. This observation agreed with previous studies [9,16,45] who determined that the optimum synergistic effect is achieved when a higher ratio of CBH to EG is used in the reaction. However, this is dependent on the nature and characteristics of the EG and the substrate used [46]. In contrast, there was no co-operation between CmixA1 and TmCel5A. CmixA1 and TmCel5A had a DS of 1.0, additionally, the total reducing sugars and glucose released were not higher than that of the CmixA1 (100%). The DS around 1.0 suggests that only CmixA1 was hydrolyzing the Avicel to produce the total reducing sugars. When combining CmixA1 with AnEG, the highest amount of total reducing sugars were produced by a 25% CmixA1:75% AnEG combination. This combination was unique, because the AnEG enzyme (at 100%) in this case displayed a higher activity compared to the optimized CmixA1 (at 100%). In addition, at 50% CmixA1:50% AnEG, the synergy displayed significantly high amounts of total reducing sugars, suggesting that both the CmixA1 and AnEG enzymes were cooperating in hydrolyzing Avicel. For CmixA1 and TrCel7B, there was no synergy, and this was supported by the DS values, which were below 1.0.

Generally, due to the high synergistic effect exhibited by this enzyme combination (CmixA1 and EGs) and the significant increase in soluble sugars released, we propose that CmixA1 (CBHI and CBHII) was the main contributor to Avicel hydrolysis and that the presence of EG induced the synergistic efficiency by shearing the β-1,4 glycosidic bonds from internal filaments, releasing smaller fragments of cellulose to provide new sites for CBH binding [16,17,46]. An alternative explanation for endo–exo synergism has been proposed by Viljamäe and coworkers [18], known as the surface erosion model. This model is based on the hypothesis that CBHI modifies the substrate structure, thereby generating obstacles that results in slowing dissociation as well as stalling itself, leading to an overall loss in catalytic efficiency. However, the eroded substrate is more accessible for EG activity, which then cleaves the substrate into smaller fragments to release the trapped CBHs [17,22]. As a result, the synergistic interaction of endo- and exo-cellulases results in the acceleration of cellulose hydrolysis [18,44].
### Table 2. Summary of the reducing sugars (RS) and glucose (Glu) released after 24 h hydrolysis of Avicel by the synergistic action of cellulases from different GH families and microbial sources.

|          | BusCel5A | TinCel7A | AnEg | TcCel7B |
|----------|----------|----------|------|---------|
| Cmix/Endo (%) | RS (mg/mL) | Glu (mg/mL) | RS (mg/mL) | Glu (mg/mL) | RS (mg/mL) | Glu (mg/mL) | RS (mg/mL) | Glu (mg/mL) |
| A1       |          |          |      |          |          |          |          |          |
| 0/100    | 0.18 ± 0.00 | 0.23 ± 0.01 | 0.00 ± 0.00 | 0.00 ± 0.00 | 1.16 ± 0.06 | 1.10 ± 0.04 | 0.45 ± 0.01 | 0.47 ± 0.02 |
| 25/75    | 0.71 ± 0.03 | 0.70 ± 0.04 | 1.19 ± 1.26 | 0.47 ± 0.01 | 1.29 ± 0.06 | 1.18 ± 0.05 | 1.08 ± 0.02 | 0.90 ± 0.88 |
| 50/50    | 0.95 ± 0.03 | 0.90 ± 0.04 | 1.30 ± 1.28 | 0.61 ± 0.02 | 1.27 ± 0.05 | 1.13 ± 0.03 | 1.15 ± 0.31 | 0.82 ± 0.05 |
| 75/25    | 1.13 ± 0.05 | 1.07 ± 0.04 | 1.38 ± 1.40 | 0.80 ± 0.03 | 1.14 ± 1.11 | 1.14 ± 0.05 | 1.15 ± 0.86 | 0.93 ± 0.96 |
| 100/0    | 0.84 ± 0.03 | 0.85 ± 0.04 | 0.84 ± 0.04 | 0.85 ± 0.04 | 0.84 ± 0.03 | 0.85 ± 0.04 | 0.84 ± 0.03 | 0.85 ± 0.04 |
| B1       |          |          |      |          |          |          |          |          |
| 0/100    | 0.18 ± 0.00 | 0.23 ± 0.01 | 0.00 ± 0.00 | 0.00 ± 0.00 | 1.16 ± 0.06 | 1.10 ± 0.04 | 0.45 ± 0.01 | 0.47 ± 0.02 |
| 25/75    | 0.25 ± 0.01 | 0.29 ± 0.01 | 0.63 ± 0.64 | 0.21 ± 0.00 | 0.98 ± 0.80 | 0.98 ± 0.04 | 0.94 ± 0.03 | 0.98 ± 0.03 |
| 50/50    | 0.31 ± 0.01 | 0.35 ± 0.01 | 0.64 ± 0.64 | 0.30 ± 0.01 | 0.94 ± 0.80 | 0.88 ± 0.04 | 0.84 ± 0.03 | 1.00 ± 0.99 |
| 75/25    | 0.37 ± 0.01 | 0.40 ± 0.02 | 0.77 ± 0.72 | 0.38 ± 0.02 | 0.41 ± 0.02 | 0.99 ± 0.91 | 0.76 ± 0.03 | 0.75 ± 0.02 |
| 100/0    | 0.40 ± 0.02 | 0.42 ± 0.02 | 0.40 ± 0.02 | 0.42 ± 0.02 | 0.40 ± 0.02 | 0.42 ± 0.02 | 0.40 ± 0.02 | 0.42 ± 0.02 |
| C1       |          |          |      |          |          |          |          |          |
| 0/100    | 0.18 ± 0.00 | 0.23 ± 0.01 | 0.00 ± 0.00 | 0.00 ± 0.00 | 1.16 ± 0.06 | 1.10 ± 0.04 | 0.45 ± 0.01 | 0.47 ± 0.02 |
| 25/75    | 0.28 ± 0.00 | 0.34 ± 0.00 | 0.72 ± 0.72 | 0.32 ± 0.01 | 0.98 ± 0.87 | 1.04 ± 0.05 | 1.00 ± 0.05 | 1.00 ± 0.05 |
| 50/50    | 0.34 ± 0.01 | 0.38 ± 0.00 | 0.76 ± 0.72 | 0.29 ± 0.01 | 0.97 ± 0.84 | 0.85 ± 0.04 | 0.80 ± 0.02 | 1.02 ± 0.98 |
| 75/25    | 0.37 ± 0.01 | 0.44 ± 0.01 | 0.88 ± 0.82 | 0.34 ± 0.01 | 0.98 ± 0.89 | 0.69 ± 0.04 | 0.66 ± 0.01 | 0.96 ± 0.03 |
| 100/0    | 0.40 ± 0.02 | 0.44 ± 0.02 | 0.40 ± 0.02 | 0.44 ± 0.02 | 0.40 ± 0.02 | 0.44 ± 0.02 | 0.40 ± 0.02 | 0.44 ± 0.02 |
| C2       |          |          |      |          |          |          |          |          |
| 0/100    | 0.18 ± 0.00 | 0.23 ± 0.01 | 0.00 ± 0.00 | 0.00 ± 0.00 | 1.16 ± 0.06 | 1.10 ± 0.05 | 0.45 ± 0.01 | 0.47 ± 0.02 |
| 25/75    | 0.14 ± 0.00 | 0.19 ± 0.00 | 0.70 ± 0.85 | 0.32 ± 0.00 | 0.96 ± 0.00 | 0.79 ± 0.04 | 0.71 ± 0.03 | 1.00 ± 1.00 |
| 50/50    | 0.13 ± 0.00 | 0.18 ± 0.00 | 0.72 ± 0.85 | 0.00 ± 0.00 | 0.53 ± 0.02 | 0.51 ± 0.02 | 0.52 ± 0.02 | 1.10 ± 1.04 |
| 75/25    | 0.10 ± 0.00 | 0.16 ± 0.00 | 0.83 ± 0.80 | 0.07 ± 0.00 | 1.20 ± 1.23 | 0.25 ± 0.00 | 0.30 ± 0.01 | 0.58 ± 0.01 |

The activity values (RS and Glu) are presented as means ± S.D. (n = 3). RS—reducing sugars, Glu—glucose, DS_{synergy} = degree of synergy for reducing sugars, DS_{glucose} = degree of synergy for glucose. CmixA1 is (TcCel7A + microbial CelA), CmixA2 is (TcCel7A + CtCel5A), CmixB1 is (HfCel2A + microbial Cel6A), CmixB2 is (HfCel7A + CtCel8A), CmixC1 is (CbCel48A + microbial Cel6A), and CmixC2 is (CbCel48A + CtCel5A). * represents the product release values that are significantly higher than those generated by the most active single enzyme.
The results obtained with CmixA2 were comparable to the synergistic relations established with CmixA1. The results showed that CmixA2 displayed the highest synergistic effect with \( Ba\text{Cel5A} \) (DS for reducing sugars: 1.47 and DS for glucose: 1.41) in a protein ratio of 75–25%. This enzyme combination (CmixA2 75%:BaEngCel5A 25%) also produced significantly more soluble sugars than the total amount produced by these enzymes individually at 100% protein loading. The highest quantity of sugars (reducing sugars: 1.43 mg/mL and glucose: 1.35 mg/mL) was also liberated by the combined activities of \( An\text{EG} \) and CmixA2 at a protein ratio of 75–25%, respectively. No synergy between CmixA2 and the other two EGs (\( Tm\text{Cel5A} \) and \( Tr\text{Cel7B} \)) was observed, which was supported by the low DS values (<1.0). We, therefore, propose that \( Trichoderma \) endoglucanases do not synergize with CmixA (both CmixA1 and CmixA2).

This further confirms the observations and hypotheses of previous researchers who stated that the free chain ends produced by the endo-glucanase, \( Tr\text{Cel7B} \), are not always accessible to CBHI [47] or that overlapping functions or competition for the same binding sites on the substrate result in antisnergy [28,48,49]. When the activity of one enzyme does not facilitate the activity of another enzyme then, antisnergy is observed (DS < or =1.0), whereas this phenomenon may also occur when competitive behavior between the enzymes is observed (enzymes competing for the same binding sites on the substrate; DS < 1.0) [48–50].

2.3.2. Synergy between CmixB1 (HjCel7A and Microbial Cel6A) or CmixB2 (HjCel7A and CtCel5A) and Various Endoglucanases

No synergism was detected between CmixB1 and any of the EGs, and the combinations did not improve the overall cellulose hydrolysis. At 100% protein loading, CmixB1 produced 0.40 mg/mL of reducing sugars and 0.42 mg/mL of glucose, which was higher than the sugars liberated by all the tested combinations. The results also showed that as the AnEG amount (%) in the enzyme combination decreased, the total amount of reducing sugars and glucose also decreased. This was a clear indication that there was no cooperation between CmixB1 and AnEG during the hydrolysis of Avicel. For synergy between CmixB1 and \( Ba\text{Cel5A}/Tm\text{Cel5A} \), a similar trend was observed in the opposite direction, whereby CmixB1 resulted in the increased sugar release from the Avicel, indicating that there was still no interaction/cooperation observed between the enzymes.

The results for CmixB2 were similar to the findings between CmixB1 and EGs. No synergism was detected between CmixB2 and any of the EGs, and the overall cellulose hydrolysis was not improved. When CmixB2 was used individually (100% protein loading), it liberated 0.40 mg/mL of reducing sugars and 0.44 mg/mL of glucose. Based on these results, we propose that that CmixB2 does not interact with any of the endo-glucanases (bacterial and fungal), and therefore, it cannot be a suitable component of the enzyme cocktail for effective biomass hydrolysis.

These results provide clear evidence that not all endo- and exo-cellulases act synergistically. One may ask why pronounced synergism was established between various combinations of EGs and \( Tl\text{Cel7A} \), but not with \( Hj\text{Cel7A} \)? What differentiates these CBHIs from the same glycoside hydrolase family (7) from each other? Various studies have reported that observed synergism could be related to their adsorption capacities. If both enzymes are weakly bound to the substrate, synergism will be shown to a much lesser degree [51]. Furthermore, we assume that these discrepancies in our results are likely due to differences in these enzymes’ specific activities on the cellulose substrate. As mentioned previously, \( Tl\text{Cel7A} \) had 2-to-3-fold higher activity on Avicel and CMC (Table 1) compared to \( Hj\text{Cel7A} \). Here, we propose that the low Avicelase activity of \( Hj\text{Cel7A} \) cannot effectively access the individual chains in the cellulose provided by EGs and is, therefore, considered rate-limiting in effective cellulose hydrolysis. This makes \( Hj\text{Cel7A} \) an unsuitable candidate in designing an optimal cellulase cocktail.
2.3.3. Synergy between CmixC1 (CsCel48A and Microbial Cel6A) or CmixC2 (CsCel48A and microbial Cel6A) and Various Endoglucanases

It was observed that CmixC1 (CsCel48A + microbial Cel6A) or EG alone at a 100% protein mass loading released the same quantity or even more sugars than their combinations. Therefore, no synergistic relationships were established between CmixC1 and any of the EGs assessed in this study. Similar results to that obtained between CmixC1 and EGs were observed when assessing the synergistic relationships between CmixC2 (CsCel48A + CtCel5A) and the EGs. It was observed that CmixC2 (CsCel48A + CtCel5A) or EG alone at a 100% protein mass loading released the same quantity or even more sugars than any of the combinations tested. Again, no synergistic relationships were established between CmixC2 and any of the EGs.

We suggest that although the endo- and exo-cellulases behaved synergistically, the overall hydrolysis was not enhanced due to the insufficient exo-cellulase activity exhibited by CsCel48A, thereby restricting the activity of the EGs to completely hydrolyze the substrate. Similar findings were reported by Irwin and coworkers [52]; however, their study assessed the synergistic relationship between fungal exo-glucanases and bacterial endo-gluconases on filter paper. The highest synergistic association (DS 1.28 and 1.24 for reducing sugars and glucose) was established when CmixC1/CmixC2 and TmCel5A were combined in a protein ratio of 75–25%. We postulate that the ability of TrCel7B to synergistically interact with CsCel48A and not with H/Cel7A, is due to the low specific activity exhibited by CsCel48A on Avicel, which agreed with a study conducted by Sánchez and coworkers [27]. They suggested that the low activity of Cel48A makes it incompatible with the conventional role of exo-cellulases, as it cannot effectively gain access in the individual chains of cellulose during cellulose hydrolysis. Thus, it is not clear whether the mechanism by which Cel7A and Cel48A synergize with other enzymes is similar. Furthermore, they found that Cel48A from T. fusca synergized well with Cel9A from T. fusca and that these two enzymes play similar roles to that of TrCel7B and TrCel7A, respectively. Thus, we assume that TrCel7B, a processive endo-cellulase, with relatively high activity on Avicel played the role of CsCel48A, this leads to noticeable synergy, but not enhanced cellulose hydrolysis. These results further support the evidence that synergy and high product formation do not always go hand-in-hand [13,53].

In contrast to the synergistic behavior observed between CmixA1/CmixA2 and BaCel5A, as well as with AnEG, CmixC1/CmixC2 displayed antisynergistic behavior. Although we postulate that this is attributed to the insufficient degree of cellulose hydrolysis displayed by CsCel48A, it remains unclear as to why a synergistic relationship would be established when CsCel48A was combined with some processive enzymes, TrCel7B or TmCel5A, but not with the other processive enzymes, AnEG and BaCel5A. These results support the evidence that the relationships between enzymes are overly complex and are highly dependent on the type of enzymes and the degree to which their activities complement each other. Therefore, there is no “guaranteed” optimal ratio of endo-cellulase/exo-cellulase for achieving the maximum degree of synergy, since the phenomenon that causes the synergistic effect depends not only on the particular enzyme classes involved but also on the nature and catalytic properties of the enzyme [43].

3. Materials and Methods

3.1. Materials

Avicel pH-101; carboxymethyl-cellulose (CMC); para-nitrophenyl substrates (p-nitrophenyl-β-D-cellobioside and -glucopyranoside); cellobiohydrolase I from Hypocrea jecorina (Cel7A); and a cellulase containing three endoglucanases (EglA (Cel9), EglB (Cel12), and EglC (Cel74)) from Aspergillus niger were purchased from Sigma Aldrich (St Louis, MO, USA). The 1,4-β-D-cellopentaitol, CBHI from Trichoderma longibrachiatum (Cel7A); CBHII from a microbial source (Cel6A); and three endoglucanases (EG) Bacillus amyloliquefaciens (Cel5A), Thermotoga maritima (Cel5A), and Trichoderma reesei (Cel7B) were purchased from Megazyme™ (Bray, CW, Ireland). CBHI from Clostridium stercolorum (Cel48A) and CBHII
from *Clostridium thermocellum* (Cel5A) were purchased from NZYTech Ltd. (Paço do Lumiar, Lisboa, Portugal), while β-glucosidase (Novozyme 188) was purchased from Novozymes (Bagsvaerd, Hovedstaden, Denmark). The enzymes used in this study were chosen according to their GH family affiliations, the source of organism (fungal or bacterial) and their commercial availability.

3.2. Protein Determination

The protein concentrations of the cellulases were determined by the Bradford method with bovine serum albumin (BSA) was used as a suitable protein standard [54].

3.3. Substrate Specificity Determination

Avicelase and endo-glucanase activities were determined using the polymeric substrates, Avicel and CMC, as described by [55]. The reactions were conducted at 37 °C for 24 and 1 h for Avicelase and CMCase assays, respectively, whereas nonreducing end-cellobiosidase activity was determined using cellopentaol, a modified oligosaccharide [55]. The 3,5-dinitrosalicylic acid (DNS) method was used for measuring the amount of reducing sugars liberated, whereby glucose was used as suitable standard [56]. Glucosidase and reducing end cellobiosidase activities were assayed using 2 mM \( p \)-nitrophenyl-β-D-glucopyranoside (\( p \)NPG) and \( p \)-nitrophenyl-β-D-cellobioside (\( p \)NPC), respectively [55]. In all studies, one unit of enzyme activity was defined as the amount of enzyme required to liberate 1 µmol of product per minute under standard assay conditions.

3.4. Synergy Studies

The synergistic relationships between the enzymes were determined by setting up various reactions containing different protein mass ratios of exo/endo- and exo-cellulases. The total protein loading for all enzyme cocktail experiments was kept at 1.375 mg protein/g of Avicel, which was supplemented with Novozyme 188 (10% mass ratio of the total protein loading) to ensure complete hydrolysis of cellobiose. The assays were carried out in 400 µL reaction volumes, containing 2% (w/v) substrate suspended in sodium citrate buffer (50 mM, pH 5.0). The reactions were conducted at 37 °C with mixing at 25 rpm for 24 h.

The hydrolysis was terminated by heating the enzymes at 100 °C for 5 min followed by cooling down at 4 °C. Hydrolysis controls included substrate (containing only the substrate without the enzyme) and enzyme controls (containing only the enzyme without the substrate). Analysis for reducing sugars and glucose released was conducted according to the methods described previously [56]. All enzyme hydrolysis assays were performed in triplicate.

3.4.1. Determination of the Optimal CBHI: CBHII Ratio (Exo–Exo Synergy) and the Effect of CBHII Swapping on Synergy

We investigated exo–exo synergy between CBHI (TlCel7A) and CBHII (microbial Cel6A) to determine the optimal CB (CBHI + CBHII) cocktail required for cellulose hydrolysis. We later swapped the microbial Cel6A (CBHII) with a CBHII from a different GH family and enzyme source (CtCel5A) to compare their hydrolysis and synergistic profile with CBHI. The ratio of CBHI:CBHII combination that resulted in increased cellulose hydrolysis was chosen as the benchmark, denoted Cmix, for subsequent experiments.

3.4.2. Synergistic Interactions between Endo- and Exo-Acting Cellulases from Different GH Families

The benchmark Cmix (CBHI (TlCel7A):CBHII (microbial Cel6A or CtCel5A)) at 75%-25% protein loading was mapped with the activities of four different EGs (BaCel5A, TmCel5A, ThCel7B, and AvCel9, 12, 74) at different protein ratios, and assessed for their capacity to liberate reducing sugars and glucose (individually and in combination) from Avicel.
3.4.3. CBHI Swapping

The CBHI (T. Cel7A) in the benchmark mixture was then swapped with a CBHI from a different GH family and/or microbial source (H. Cel7A or C. Cel48A) to assess whether this approach of CBHI swapping had any influence on the synergism established between endo- and exo-cellulases. The ratio of 75%-25% protein loading between CBHI: CBHII was kept consistent throughout all the experiments.

3.4.4. Calculation of the Degree of Synergy (DS)

The degree of synergy was calculated as the ratio between the observed activity produced by the combination of enzymes performing in synergy to the sum of the activities produced by the individual enzymes [23,46].

\[
DS = \frac{\text{(observed activity of combined enzyme 1 & 2)}}{\left(\text{activity of enzyme 1}\right) + \left(\text{activity of enzyme 2}\right)}
\]

The three outcomes for DS are: (i) DS > 1.0, enzymes act synergistically to degrade a substrate; (ii) DS = 1.0, no synergy, and (iii) DS < 1.0, enzymes do not interact synergistically, which could be a result of competitive behavior [13,49].

3.5. Data Analysis

One-way analysis of variance (ANOVA) was used for the evaluation of significant increase in activity exhibited by enzyme combinations (considered with respect to reducing sugars and glucose released) compared to the theoretical sum of the individual enzyme controls for each combination. All pairwise comparison procedures were based at 95% and 99% confidence level (\(p < 0.01\) and \(0.05\)) and were conducted using the Data Analysis feature in Microsoft Excel 2016 (Redmond, WA, USA).

4. Conclusions

In this investigation, cross synergism was explored by swapping various endo- and exo-cellulases from different GH families and mapping their activity at different protein ratios. The results showed that CmixA2 displayed the highest synergistic effect with BaCel5A (DS for reducing sugars: 1.47; DS for glucose: 1.41) in a protein ratio of 75–25%. The different family GHs were successfully characterized with respect to their biochemical characteristics. It was evident that although the enzymes are substrate specific (based on their 3D structure and sequence similarity), it is apparent that some endo-glucanases may have dual functions due to their processive nature, thus, they display both endo- and exo-glucanase activity. Synergy studies showed that swapping CBHII had minor effects on the synergistic and hydrolysis patterns observed between cellobiohydrolases, suggesting that CBHIII enzymes might share similar catalytic mechanisms. On the other hand, CBHI swapping exhibited drastic changes even for same GH family CBHs. It was also shown that synergy between endo- and exo-glucanases is not always achieved; it seemed the synergistic effect depends not only on the enzyme class but also on the nature of the enzymes involved. We, therefore, postulate that due to the different substrate specificities exhibited by cellulases from different GH family affiliations and microbial sources, enzymes are not always compatible with each other for efficient cellulose degradation. It appears that only by examining the specific activities of an enzyme (individually and in combination), we can substantiate whether an enzyme/enzyme cocktail will offer any advantages towards enhancing cellulose hydrolysis.

Author Contributions: Conceptualization, M.T., S.M., M.S.M., and B.I.P.; methodology, S.M., M.T., M.S.M., and B.I.P.; software, M.T. and S.M.; validation, M.T., S.M., M.S.M., and B.I.P.; formal analysis, M.T., S.M., and B.I.P.; investigation, M.T.; resources, B.I.P.; data curation, M.T., S.M., M.S.M., and B.I.P.; writing—original draft preparation, M.T.; writing—review and editing, M.T., S.M., M.S.M., and B.I.P.; visualization, M.T., S.M., and B.I.P.; supervision, S.M. and B.I.P.; project administration, B.I.P.; funding acquisition, B.I.P. All authors have read and agreed to the published version of the manuscript.
Funding: Financial support from the National Research Foundation (NRF), Department of Science & Technology of South Africa and Rhodes University is gratefully acknowledged. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s), and therefore, the NRF does not accept any liability in regard thereto.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to reasons of privacy.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References
1. Lynd, L.R.; Weimer, P.J.; Van Zyl, W.H.; Pretorius, I.S. Microbial cellulose utilization: Fundamentals and biotechnology. Microbiol. Mol. Biol. Rev. 2002, 66, 506–577. [CrossRef] [PubMed]
2. Zhang, X.; Wang, S.; Wu, X.; Liu, S.; Li, D.; Xu, H.; Gao, P.; Chen, G.; Wang, L. Subsite-specific contributions of different aromatic residues in the active site architecture of glycoside hydrolase family 12. Sci. Rep. 2015, 4, 1–12. [CrossRef] [PubMed]
3. Leis, B.; Held, C.; Bergkemper, F.; Dennemarck, K.; Steinbauer, R.; Reiter, A.; Mechelke, M.; Moerch, M.; Graubner, S.; Liebl, W.; et al. Comparative characterization of all celulosomal cellulosomes from Clostridium thermocellum reveals high diversity in endoglucanase product formation essential for complex activity. Biotechnol. Biofuels 2017, 10, 240. [CrossRef] [PubMed]
4. Vlasenko, E.; Schulein, M.; Cherry, J.; Xu, F. Substrate specificity of family 5, 6, 7, 9, 12, and 45 endoglucanases. Bioresour. Technol. 2010, 101, 2405–2411. [CrossRef] [PubMed]
5. Chen, Z.; Friedland, G.D.; Pereira, J.H.; Reveco, S.A.; Chan, R.; Park, J.I.; Thelen, M.P.; Adams, P.D.; Arkin, A.P.; Keasling, J.D.; et al. Tracing determinants of dual substrate specificity in glycoside hydrolase family 5. J. Biol. Chem. 2012, 287, 25335–25343. [CrossRef] [PubMed]
6. Rauwerdink, A.; Kazlauskas, R.J. How the same core catalytic machinery catalyzes 17 different reactions: The serine-histidine-aspartate catalytic triad of α/β-hydrolase fold enzymes. ACS Catal. 2015, 5, 6153–6176. [CrossRef] [PubMed]
7. Horn, S.J.; Vaa-Je-Kolstad, G.; Westereng, B.; Eijsink, V.G. Novel enzymes for the degradation of cellulose. Biotechnol. Biofuels 2012, 5, 45. [CrossRef] [PubMed]
8. Teeri, T.T. Crystalline cellulose degradation: New insight into the function of celllobiohydrolases. Trends Biotechnol. 1997, 15, 160–167. [CrossRef] [PubMed]
9. Den Haan, R.; Van Zyl, J.M.; Harms, T.M.; Van Zyl, W.H. Modeling the minimum enzymatic requirements for optimal cellulose conversion. Environ. Res. Lett. 2013, 8, 025013. [CrossRef] [PubMed]
10. Ganner, T.; Bubner, P.; Eibinger, M.; Maryhofer, C.; Plank, H.; Nidetzky, B. Dissecting and reconstructing synergism in situ visualization of cooperativity among cellulases. J. Biol. Chem. 2012, 287, 43215–43222. [CrossRef] [PubMed]
11. Fang, H.; Zhao, R.; Li, C.; Zhao, C. Simultaneous enhancement of the beta-exo synergism and exo-exo synergism in Trichoderma reesei cellulase to increase the cellulose degrading capability. Microb. Cell Fact. 2019, 18, 9. [CrossRef] [PubMed]
12. Malgas, S.; Thoresen, M.; Van Dyk, J.S.; Pletschke, B.I. Time dependence of enzyme synergism during the degradation of model and natural lignocellulosic substrates. Enzyme Microb. Technol. 2017, 103, 1–11. [CrossRef] [PubMed]
13. Van Dyk, J.S.; Pletschke, B.I. A review of lignocellulose bioconversion using enzymatic hydrolysis and synergistic cooperation between enzymes- factors affecting enzyme, conversion and synergy. Biotechnol. Adv. 2012, 30, 1458–1480. [CrossRef] [PubMed]
14. Arfi, Y.; Shamsboum, A.; Rogachev, I.; Peleg, T.; Bater, E.A. Integration of bacterial lytic polysaccharide monooxygenases into designer cellulosomes promotes enhanced cellulose degradation. Proc. Natl. Acad. Sci. USA 2014, 111, 9109–9114. [CrossRef] [PubMed]
15. Peciulyte, A.; Karlstrom, K.; Larsson, P.T.; Olson, L. Impact of supramolecular structure of cellulose on the efficiency of the enzymatic hydrolysis. Biotechnol. Biofuels 2015, 8, 58. [CrossRef]
16. Henriassat, B.; Driguez, H.; Viet, C.; Schülein, M. Synergism of cellulases from Trichoderma reesei in the degradation of cellulose. Biotechnology 1985, 3, 722–726. [CrossRef] [PubMed]
17. Jalak, J.; Kurašín, M.; Teugas, H.; Väljamäe, P. Endo-exo synergism in cellulose hydrolysis revisited. J. Biol. Chem. 2012, 287, 28802–28815. [CrossRef] [PubMed]
18. Väljamäe, P.; Sild, V.; Nutt, A.; Pettersson, G.; Johansson, G. Acid hydrolysis of bacterial cellulose reveals different modes of synergistic action between cellulbiohydrolyse I and endoglucanase. Eur. J. Biochem. 1999, 266, 327–334. [CrossRef] [PubMed]
19. Zhang, Y.H.; Lynd, L.R. Toward an aggregated understanding of enzymatic hydrolysis of cellulose. Non-complexed cellulase systems. Biotechnol. Bioeng. 2004, 88, 797–824. [CrossRef] [PubMed]
20. Kostylev, M.; Wilson, D. Synergistic interactions in cellulose hydrolysis. Biofuels 2012, 3, 61–70. [CrossRef] [PubMed]
21. Adsul, M.; Sandhu, S.K.; Singhania, R.R.; Gupta, R.; Puri, S.K.; Mathur, A. Designing a cellulosytic enzyme cocktail for the efficient and economical conversion of lignocellulosic biomass to biofuels. Enzym. Microb. Technol. 2019, 133, 109442. [CrossRef] [PubMed]
22. Kurašín, M.; Väljamäe, P. Processivity of celllobiohydrolases is limited by the substrate. J. Biol. Chem. 2011, 286, 169–177. [CrossRef] [PubMed]
23. Yang, M.; Zhang, Z.D.; Zhang, P.Y.; Zhou, X.; Ma, X.Q.; Li, F.L. Synergistic cellulose hydrolysis dominated by a multi modular processive endoglucanase from Clostridium cellulosi. Front. Microbiol. 2016, 7, 932. [CrossRef]
24. Berger, E.; Zhang, D.; Zverlov, V.V.; Schwarz, W.H. Two noncellulosomal cellulosomes of Clostridium thermocellum, Cel9I and Cel48Y, hydrolyze crystalline cellulose synergistically. *FEMS Microbiol. Lett.* 2007, 268, 194–201. [CrossRef] [PubMed]

25. Irwin, D.C.; Zhang, A.; Wilson, D.B. Cloning, expression and characterization of a family 48 exocellulase, Cel48A, from Thermobifida fusca. *Eur. J. Biochem.* 2000, 267, 4988–4997. [CrossRef]

26. Kostylev, M.; Wilson, D. A distinct model of synergism between processive endocellulases (TfCel9A) and exocellulase (TfCel48A) from Thermobifida fusca. *Appl. Environ. Microbiol.* 2014, 80, 339–344. [CrossRef]

27. Sánchez, M.M.; Irwin, D.C.; Pastor, F.I.J.; Wilson, D.B.; Díaz, P. Synergistic activity of Paenibacillus sp. BP-23 cellbiohydrolase Cel48C in association with the contiguous endoglucanase Cel9B and with endo- or exo-acting glucanases from *Thermobifida fusca*. *Biotechnol. Bioeng.* 2004, 87, 161–169. [CrossRef]

28. Guimarães, B.G.; Souchon, H.; Lytle, B.L.; David, W.; Alzari, P.M. The crystal structure and catalytic mechanism of cellbiohydrolase Cel5, the major enzymatic component of *Clostridium thermocellum* cellulosome. *J. Mol. Biol.* 2002, 320, 587–596. [CrossRef]

29. Parsieglia, G.; Juy, M.; Reverbel-Leroy, C.; Tardif, C.; Belaich, A.; Belaich, J.P.; Tardif, C. The processive endocellulase CelF, a major component of the *Clostridium cellulolyticum* cellulosome: Purification and characterization of the recombinant form. *J. Bacteriol.* 1997, 179, 46–52. [CrossRef]

30. Billard, H.; Faraj, A.; Ferreira, N.L.; Blanquet, S.H. Optimization of a synthetic mixture of major *Trichoderma reesei* enzymes for the hydrolysis of steam-exploded wheat straw. *Biotechnol. Biofuels* 2012, 5, 9. [CrossRef] [PubMed]

31. Tomme, P.; Van Tilbeurgh, H.; Pettersson, G.; Van Damme, J.; Vandekerckhove, J.; Knowles, J.; Teeri, T.; Claeyssens, M. Studies of *Clostridium thermocellum*: Role of carbohydrate binding module and the endo-lytic character of the enzymes. *Biotechnol. Bioeng.* 2003, 87, 1639–1647. [CrossRef] [PubMed]

32. Zverlov, V.V.; Velikodvorskave, G.A.; Schwarz, W.H. Two new cellulolosome components encoded downstream of CelI in the *Clostridium thermocellum* genome. *FEBS J.* 1999, 268, 1069–1077. [CrossRef] [PubMed]

33. Bróx, J.L.; Cartmell, A.; Carvalho, A.L.; Verzé, G.; Bayer, E.A.; Vazana, Y.; Correia, M.A.; Prates, J.A.; Ratnaparkhe, S.; Boraston, A.B.; et al. Structural insights into a unique cellulosomal fold and mechanism of cellulosome hydrolysis. *Proc. Natl. Acad. Sci. USA* 2011, 108, 5237–5242. [CrossRef]
48. Converse, A.O.; Optekar, J.D. A synergistic kinetics model for enzymatic cellulose compared to degree-of-synergism experimental results. Biotechnol. Bioeng. 1993, 42, 145–148. [CrossRef]
49. Mafa, M.; Malgas, S.M.; Rashamushe, K.; Pletschke, B.I. Delineating functional properties of a cello-oligosaccharide and \( \beta \)-glucan specific cellbiohydrolase (GH5_38): Its synergism with Cel6A and Cel7A for \( \beta \)-(1,3)-(1,4)-\( \beta \)-glucan degradation. Carbohydr. Res. 2020, 495, 108081. [CrossRef]
50. Malgas, S.; Van Dyk, J.S.; Pletschke, B.I. \( \beta \)-Mannanase (Man26A) and \( \alpha \)-galactosidase (Aga27A) synergism—A key factor for the hydrolysis of galactomannan substrates. Enzyme Microb. Technol. 2015, 70, 1–8. [CrossRef]
51. Wood, T.M.; McCrae, S.; Bhat, K.M. The mechanism of fungal cellulase action. Synergism between enzyme components of \textit{Penicillium pinophilum} cellulase in solubilizing hydrogen bond ordered cellulose. Biochem. J. 1989, 260, 37–43. [CrossRef] [PubMed]
52. Irwin, D.C.; Spezio, M.; Walker, L.P.; Wilson, D.B. Activity studies of eight purified cellulases. Specificity, synergism, and binding domain effects. Biotechnol. Bioeng. 1983, 42, 1002–1013. [CrossRef]
53. Andersen, N.; Johansen, K.S.; Michelsen, M.; Stenby, E.H.; Krogh, K.B.R.M.; Olsson, L. Hydrolysis of cellulose using mono-component enzymes shows synergy during hydrolysis of phosphoric acid swollen cellulose (PASC), but competition on Avicel. Enzyme Microb. Technol. 2008, 32, 362–370. [CrossRef]
54. Bradford, M.M. A rapid and sensitive for the quantification of microgram quantities of proteins utilizing the principle of protein-dye binding. Anal. Biochem. 1976, 72, 248–254. [CrossRef]
55. Malgas, S.; Chandra, R.; Van Dyk, J.S.; Saddler, J.N.; Pletschke, B.I. Formulation of an optimized synergistic enzyme cocktail, Holomix, for effective degradation of various pre-treated hardwoods. Bioresour. Technol. 2017, 245, 52–65. [CrossRef]
56. Miller, G.I. Use of dinitrosalicylic acid reagent for the determination of reducing sugars. Anal. Chem. 1959, 72, 426–428. [CrossRef]