Surface Display of Small Affinity Proteins on *Synechocystis* sp. Strain PCC 6803 Mediated by Fusion to the Major Type IV Pilin PilA1

Ivana Cengic,a Mathias Uhlén,a,b Elton P. Hudsona

aSchool of Engineering Sciences in Chemistry, Biotechnology, and Health, KTH Royal Institute of Technology, Science for Life Laboratory, Stockholm, Sweden
bNovo Nordisk Foundation Center for Biosustainability, Technical University of Denmark, Hørsholm, Denmark

**ABSTRACT** Functional surface display of small affinity proteins, namely, affibodies (6.5 kDa), was evaluated for the model cyanobacterium *Synechocystis* sp. strain PCC 6803 through anchoring to native surface structures. These structures included confirmed or putative subunits of the type IV pili, the S-layer protein, and the heterologous *Escherichia coli* autotransporter antigen 43 system. The most stable display system was determined to be through C-terminal fusion to PilA1, the major type IV pilus subunit in *Synechocystis*, in a strain unable to retract these pili (Δ*pilT1*). Type IV pilus synthesis was upheld, albeit reduced, when fusion proteins were incorporated. However, pilus-mediated functions, such as motility and transformational competency, were negatively affected. Display of affibodies on *Synechocystis* and the complementary anti-idiotypic affibodies on *E. coli* or *Staphylococcus carnosus* was able to mediate interspecies cell-cell binding by affibody complex formation. The same strategy, however, was not able to drive cell-cell binding and aggregation of *Synechocystis*-only mixtures. Successful affibody tagging of the putative minor pilin PilA4 showed that it locates to the type IV pili in *Synechocystis* and that its extracellular availability depends on PilA1. In addition, affibody tagging of the S-layer protein indicated that the domains responsible for the anchoring and secretion of this protein are located at the N and C termini, respectively. This study can serve as a basis for future surface display of proteins on *Synechocystis* for biotechnological applications.

**IMPORTANCE** Cyanobacteria are gaining interest for their potential as autotrophic cell factories. Development of efficient surface display strategies could improve their suitability for large-scale applications by providing options for designed microbial consortia, cell immobilization, and biomass harvesting. Here, surface display of small affinity proteins was realized by fusing them to the major subunit of the native type IV pili in *Synechocystis* sp. strain PCC 6803. The display of complementary affinity proteins allowed specific cell-cell binding between *Synechocystis* and *Escherichia coli* or *Staphylococcus carnosus*. Additionally, successful tagging of the putative pilin PilA4 helped determine its localization to the type IV pili. Analogous tagging of the S-layer protein shed light on the regions involved in its secretion and surface anchoring.

**KEYWORDS** surface display, cyanobacteria, affibody, type IV pili, S-layer protein, cell-cell binding

*Cyanobacteria* are emerging as attractive alternative microbial production hosts for the photosynthesis-driven conversion of CO₂ to biofuels and platform chemicals (1–3). *Synechocystis* sp. strain PCC 6803 has emerged as a model organism; however, many biotechnological tools available for other commonly engineered microbes, such
as *Escherichia coli* and *Saccharomyces cerevisiae*, are still underdeveloped for cyanobacteria. One such tool is a surface display platform, where the diverse range of applications (4) can be useful for optimizing aspects of microbial production hosts. For example, surface display of polymerizing proteins on different organisms could aid in constructing synthetic microbial communities and engineered biofilm structures. The development of synthetic consortia has gained interest due to its potential for creating more complex and robust systems, which could aid in, e.g., biofuel production applications (5). Here, cyanobacteria could produce the sugars required by engineered heterotrophs (6–8). Display of polymerizing proteins could also be used for controlled flocculation by self-aggregation and thus facilitate harvesting of biomass without the need for externally added flocculants (9, 10). This could help avoid chemical contamination of the biomass and growth media while also reducing harvesting costs.

Multiple aspects of cyanobacteria challenge the realization of useful surface display systems. These Gram-negative bacteria have an unusually thick and highly cross-linked peptidoglycan layer (11). In addition, the intracellular thylakoid membranes could become targets for incorrect anchor insertion (12). Many species also synthesize and assemble protective extracellular S-layers (13) and secrete polysaccharide substances that form cell-enveloping capsules, sheaths, or slimes (14). Native proteins could be advantageous as carriers for functional display since they are already capable of successfully navigating the complex cell wall structure of cyanobacteria. Surface structures commonly used as carriers in other bacteria include subunits of polymeric surface appendages such as pili or flagella, S-layer proteins, or outer membrane proteins (4).

Some success in surface display on cyanobacteria has been reported. Organophosphorus hydrolase from *Flavobacterium* sp. was displayed on *Synechococcus elongatus* PCC 7942 using the truncated ice nucleation protein from *Pseudomonas syringae* (15) as well as through a truncating insertion into a proposed extracellular loop of the native porin SomA (16). However, in both cases, the hydrolase was only partially accessible to proteases targeting extracellular structures, suggesting incomplete display. Recently, the successful display of a FLAG epitope on *S. elongatus* was realized by sandwich insertion into a predicted extracellular loop of SomA (17). The extracellular display of the FLAG epitope and the external addition of an anti-FLAG antibody were able to mediate adherence between *S. elongatus* and protein A-expressing yeast or protein A-coupled beads (17). In *Synechocystis*, a surface display method utilizing *E. coli* antigen 43, an autotransporter protein, was able to display the native antigen 43 passenger domain (18).

In this work, several native surface structures on *Synechocystis* sp. PCC 6803 were explored as possible carrier proteins to mediate the surface display of a 6.5-kDa affibody (19). Affibodies are small (6.5-kDa) engineered affinity proteins with exceptional stability and rapid folding (19). They are based on the immunoglobulin-binding B domain of staphylococcal protein A (20). In this work, the carriers evaluated for allowing surface display included the S-layer protein (21), the major type IV pilus subunit PilA1 (22), and the two putative pilin proteins PilA2 and PilA4 (23). In addition, display using the heterologous *E. coli* antigen 43 autotransporter was also evaluated. Our established display system was further tested for its ability to mediate inter- and intraspecies cell-cell binding due to the display of complementary complex-forming affibodies.

**RESULTS**

Selection of surface structures to evaluate as carrier proteins. *Synechocystis* cells are covered in protruding appendages of both thick and thin morphologies (22). The thick appendages have been classified as type IV pili and are important for motility and natural transformation competency (22, 23). Successful fusion to the protein subunits of the pilus could provide a high level of surface display due to its polymeric nature. The major pilin protein, which makes up the majority of the type IV pilus structure, has been identified in *Synechocystis* as PilA1 (*sll1694* product) (22). There are nine additional...
genes in the Synechocystis genome displaying prepilin gene characteristics (24). The putative pilin PilA2 (sll1695 product) is transcribed from the same operon as PilA1, and together, they are the Synechocystis pilins showing the highest similarity to the major pilin protein in the highly characterized pilus structures of Pseudomonas aeruginosa and Myxococcus xanthus (25). Upregulated transcription of both pilA1 and pilA4 (sll1456) has been observed upon exposure to external stresses such as butanol (26), benzyl alcohol (27), and carbon limitation (28), indicating potentially concerted expression. These three pilin proteins (PilA1, PilA2, and PilA4) were chosen as potential carrier proteins for evaluation of the surface display of affibodies.

The S-layer protein (sll1951 product) of Synechocystis is the only component of its paracrystalline S-layer, which makes up the outermost cell surface (21). Successful fusion to the S-layer protein could provide a cell completely covered in fusion proteins, and it was therefore included in the set of carrier proteins for evaluation.

Outer membrane proteins are common carriers that allow the covalent anchoring of displayed proteins on the cell surface (4). The E. coli antigen 43 autotransporter system has previously been successfully expressed in Synechocystis, where it was able to mediate the display of its native passenger domain (18). Here, the antigen 43 system was thus evaluated for its ability to instead mediate the display of an affibody as the passenger.

A schematic showing the cell wall architecture of Synechocystis as well as the location of the proteins evaluated as carriers for surface display is shown in Fig. 1A.

**Construction and confirmed expression of carrier-passenger fusion proteins.** The affibody ZTaq S1-1 (here ZTaq) (29) was used as the passenger protein in this study. Fusions between the selected carriers and the ZTaq passenger were done by either N- or C-terminal fusion, depending on the characteristics of the carrier (Fig. 1B to D and Table 1). A flexible linker region (GSSSGSS) was included between the fused proteins to avoid potential structural disruption. All constructed fusion proteins were expressed under the control of the moderate P-psbA2 promoter (30), from a replicative plasmid. A nonmotile Synechocystis strain was used as the main host in this study.

For all evaluated pilins (PilA1, PilA2, and PilA4), the ZTaq fusion occurred at their C termini (Fig. 1B), as prepilins have N-terminal signal peptides that are cleaved off.
by PilD during their maturation into pilins (24). In addition, the N-terminal part of the mature pilin forms a hydrophobic helix that is embedded in the middle of the helical pilus rod (31), making fusion to the N terminus unsuitable for display purposes.

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Secretion of the S-layer protein (here Slp) in *Synechocystis* has been shown to be dependent on the TolC homolog Slr1270 (32) and, recently, two more accessory proteins of the type I secretion system (33). In addition, Slp is a member of the RTX (repeat-in-toxin) protein family, which is known to be secreted by the type I secretion system that utilizes noncleavable C-terminal signal peptides (34). However, the actual signal peptide for Slp in *Synechocystis* has not yet been described. Therefore, evaluating Slp as a carrier for surface display included fusing Z_Taq to either the C or N terminus (Fig. 1B and C). During the construction of the Slp fusion proteins, a frameshift resulting from a 76-bp deletion (bp 3127 to 3202) was discovered in the *sll1951* gene of the wild-type *Synechocystis* host used. Microevolution within the gene for Slp (*sll1951*) was observed previously in resequencing efforts for various laboratory *Synechocystis* strains (35, 36).

The correct full-length gene, as specified by Cyanobase (37), was therefore amplified from another available wild-type strain.

For the heterologous *E. coli* antigen 43 system, the native passenger domain (amino acids 53 to 551) was exchanged for Z_Taq (Fig. 1D). The β-chain translocator domain was kept intact, as was the antigen 43 signal peptide, which was shown to mediate correct translocation in *Synechocystis* previously (18).

Functional expression of the correct Z_Taq-carrier fusion proteins in *Synechocystis* was evaluated by immunoblotting against the Z_Taq affibody (Fig. 1E). A strain expressing Z_Taq intracellularly was included as a positive control. The blots show a high degree of unspecific binding; however, comparison to the wild-type controls allowed the identification of the Z_Taq fusion proteins. All pilin-based fusion proteins showed bands of a larger-than-expected size (22.3 kDa for PilA1-Z_Taq, 22.9 kDa for PilA2-Z_Taq, and 23.6 kDa for PilA4-Z_Taq), even when accounting for predicted signal peptides (see Materials and Methods). PilA1 in *Synechocystis* undergoes several posttranslational modifications that are important for pilus assembly and function (38–40). It is possible that similar modifications also occur on PilA2 and PilA4, thus yielding larger-than-expected sizes for the fusion proteins. The multiple bands seen for PilA1-Z_Taq and PilA4-Z_Taq can also be explained by an incomplete modification of some of the protein pool. Both N- and C-terminal versions of the Slp-based Z_Taq fusion proteins were detected, whereby two bands were observed for the Z_Taq-Slp strain (Fig. 1E). This indicates that the Z_Taq-Slp but not the Slp-Z_Taq fusion protein was able to undergo the glycosylation that is found on native Slp (21). Some degradation products could also be seen for the PilA1-Z_TaqPilA4-Z_Taq and Z_Taq-Slp strains. The heterologous antigen 43-Z_Taq strain yielded a band at the expected size (58.7 kDa), indicating the correct assembly of the fusion protein (Fig. 1E).

**Assessing surface display of Z_Taq on Synechocystis by flow cytometry and immunofluorescence.** The *Synechocystis* strains expressing Z_Taq fusion proteins were analyzed by flow cytometry to measure the surface availability of Z_Taq to an antiaffibody antibody. For a representative image of the gating procedure used to select the cyanobacterial population, see Fig. S1A in the supplemental material. The measured median fluorescence intensity (MFI) for all strains was normalized to the value obtained for a wild-type control, yielding relative MFI values. Analysis by immunofluorescence was also included in order to provide a visual comparison between strains and gauge the location of the Z_Taq affibody on the cells. More representative micrographs, in addition to the ones shown in Fig. 2, are shown in Fig. S2 in the supplemental material.

The construct using antigen 43 as a carrier did not mediate surface availability of the affibody but yielded only roughly background fluorescence levels (Fig. 2A and B). In contrast, fusion to PilA1 or PilA4 yielded a >2-fold increase in the relative MFI signal (Fig. 2A) and comparable labeling in the immunofluorescence assay (Fig. 2B). The use of PilA2 as a carrier also resulted in labeled cells when viewed with a microscope but at a smaller amount than for either PilA1-Z_Taq or PilA4-Z_Taq. The measured relative MFI for PilA2-Z_Taq reflected this lower display level by resulting in close-to-background fluorescence levels (Fig. 2A). For Slp, the fusion of Z_Taq to its N terminus (Z_Taq-Slp) gave a 10-fold increase and the highest relative MFI signal of all evaluated strains, while fusion to the C terminus (Slp-Z_Taq) showed a much lower level of functional display. In
addition, immunofluorescence analysis showed that the ZTaq-Slp fusion proteins were able to assemble into cell-enveloping S-layer structures (Fig. 2B). The collected flow cytometry data were also analyzed in terms of the percentage of labeled, and, thus, ZTaq-displaying, cells within the studied populations (see Fig. S1B and S1C in the supplemental material for an example of the gating procedure). Approximately 50% of the PilA1-ZTaq and PilA4-ZTaq cells and 95% of the ZTaq-Slp cells displayed the affibody (Fig. S3A). While labeled cells were visible within the PilA2-ZTaq and Slp-ZTaq populations by immunofluorescence, the percentage of labeled cells, as determined by flow cytometry, was less than 5%. Collectively, these results show that C-terminal fusions to the pilin proteins PilA1 and PilA4, as well as N-terminal fusion to Slp, were able to mediate the most promising levels of functional display and extracellular availability of ZTaq.

**FIG 2** Detection of surface-displayed ZTaq on Synechocystis cells via flow cytometry and immunofluorescence analysis. An antiaffibody antibody and a secondary antibody labeled with Alexa Fluor 488 were used for detection. For the flow cytometry analysis (A, C, and E), the obtained median fluorescence intensity (MFI) values were normalized to that of the wild-type control, resulting in relative MFI values. All flow cytometry data are presented as averages ± standard deviations from four independent experiments. For the immunofluorescence analysis (B, D, and F), representative images of labeled, if present, Synechocystis cells are shown. The cells were analyzed for autofluorescence (chlorophyll a) (Texas Red filter) and ZTaq display (Alexa Fluor 488) (GFP filter) (bars, 2 μm). (A and B) Evaluation of ZTaq display levels for all selected potential native (PilA1, PilA2, PilA4, and Slp) and heterologous (antigen 43) carrier proteins. A control expressing ZTaq intracellularly was included. An additional wild-type control for immunofluorescence is shown. (C and D) Evaluation of ZTaq display levels for PilA1-ZTaq strains with knockouts of pilA1 or pilT1. Controls (ZTaq ΔpilT1 and ΔpilT1) were also evaluated. (E and F) Evaluation of ZTaq display levels for PilA4-ZTaq strains with knockouts of pilA4 or pilT1. Controls (ZTaq ΔpilA4 and ΔpilA4) were also evaluated.
In common for PilA1, PilA4, and Slp is that they are confirmed or putative subunits of externally accessible structures of the cell (Fig. 1A). We speculated that the S-layer could form a physical barrier that hinders membrane-integrated antigen 43 to mediate the accessible display of ZTaq; this was found to be the case for a porin-based display system in *S. elongatus* (17). However, later results showed that the wild-type *Synechocystis* strain used in this study lacks an external S-layer, most likely due to the identified 76-bp deletion in its gene, meaning that no possibly occluding S-layer was present. We conclude that antigen 43 was not able to display ZTaq on the cell surface.

Improving ZTaq display for the carrier proteins PilA1 and PilA4. We next attempted to improve the display efficiency of the PilA1-ZTaq and PilA4-ZTaq strains to levels similar to that of the ZTaq-Slp strain. In an attempt to replace all native proteins with ZTaq fusion variants, *pilA1* (*sll1694*) and *pilA4* (*slr1456*) gene knockouts were introduced into the respective strains. In addition, the knockout of *pilT1* (*slr0161*) was evaluated for both strains. PilT1 is an ATPase responsible for the retraction, by ATP-driven depolymerization, of type IV pili in *Synechocystis* (41). Disruption of *pilT1* yields a nonmotile and hyperpiliated phenotype (22, 41). This hyperpiliation could lead to an increase in the number of surface-exposed ZTaq molecules when fused to pilus subunits.

A PilA1-ZTaq ΔpilA1 strain had reduced ZTaq display (Fig. 2C and D), indicating that the presence of native PilA1 is required to uphold the functional assembly of the pilus structure. ΔpilA1 and ZTaq ΔpilA1 controls were not included for analysis due to clumping during cultivation; this phenotype was described previously for ΔpilA1 strains (23). Knockout of *pilT1* in the PilA1-ZTaq ΔpilT1 strain increased ZTaq display more than 2-fold, as measured by relative MFI (Fig. 2C) and as seen by immunofluorescence (Fig. 2D). In addition, the micrographs of the PilA1-ZTaq ΔpilT1 strain showed cells surrounded by fluorescent extending bundles of pili (Fig. 2D; see also Fig. S2B in the supplemental material), supporting that pilus synthesis could take place while incorporating the fusion protein. The percentage of labeled and displaying cells within the PilA1-ZTaq ΔpilT1 population improved to 87% (Fig. S3B).

Disruption of *pilA4* in the PilA4-ZTaq ΔpilA4 strain did not affect ZTaq display (Fig. 2E and F). Surprisingly, disruption of *pilT1* in the PilA4-ZTaq ΔpilT1 strain led to a nearly complete loss of ZTaq display. The same effect was evident in the reduced number of labeled cells within the PilA4-ZTaq ΔpilT1 population (Fig. S3C). To evaluate if the extracellular display of the PilA4-ZTaq protein is associated with the type IV pili, a knockout of *pilA1* was carried out. Deletion of the gene for this major pilin (*pilA1*) leads to the loss of type IV pili on *Synechocystis* (22, 23). The PilA4-ZTaq ΔpilA1 strain lost ZTaq display (Fig. 2E and F and Fig. S3C), supporting that PilA4-ZTaq and possibly, by extension, PilA4 are dependent on the major pilin PilA1 or functional type IV pilus assembly for extracellular availability. In several instances, the fluorescence in the micrographs for the PilA4-ZTaq base strain was localized to pilus-like structures extending from the cells (Fig. S4), further supporting that PilA4-ZTaq is directly incorporated into the pili. In light of this, the contrasting results for *pilT1* disruption in the PilA1-ZTaq and PilA4-ZTaq base strains are unexpected, potentially indicating divergent regulation for PilA4 and PilA1.

Effect on pilus and S-layer assembly due to incorporation of ZTaq fusion proteins. The two best-performing ZTaq display systems (ZTaq-Slp and PilA1-ZTaq ΔpilT1) have been shown to allow the extracellular availability of the ZTaq fusion proteins. Although these strains were able to incorporate fusion proteins into the relevant surface structures (Fig. 2B and D), it was unclear if this nevertheless contributed negatively to the stability and assembly of these structures. To study this, the relative extracellular protein amounts of these structures were quantified. Protein fractions from the cell surface and culture media of selected strains were isolated and analyzed by SDS-PAGE and immunoblotting against ZTaq. Fractions containing the cell surface-associated pili were obtained by shearing the pili off the cells by vortexing, an established method for isolation of pili (42). S-layer surface fractions were isolated by...
treating cells with EGTA, allowing the removal of the Ca$^{2+}$ ions thought to stabilize the S-layer (34). In addition, the collected medium fractions were subjected to protein precipitation to concentrate any proteins shed off from the cells during cultivation. Analysis of the pilin protein amounts showed that fewer pilins could be recovered from PilA1-ZTaq than from the wild type (Fig. 3A). The PilA1-ZTaq ΔpilT1 strain allowed higher recovery of pilins than the base strain PilA1-ZTaq (Fig. 3A), in agreement with the flow cytometry and immunofluorescence results (Fig. 2C and D); however, the amount of isolated pilins did not reach the same level as for the ΔpilT1 background strain. The reduced amounts of extractable cell surface-associated pili in both PilA1-ZTaq-expressing strains, compared to the amounts in their background strains, indicate that although type IV pilus synthesis was possible while incorporating the fusion proteins, it was also negatively affected by it. The immunofluorescence micrographs of the PilA1-ZTaq base strain (Fig. 2B; see also Fig. S2A in the supplemental material) show fluorescence mainly close to the cell surface rather than in extending pilus-like structures. This indicates a potential truncation of the pili due to PilA1-ZTaq incorporation, explaining the smaller amount of recovered extracellular pili from these strains. The two control strains (ΔpilA1 and ΔpilT1) showed, as expected, no recoverable pilins and hyperpiliation, respectively (Fig. 3A). The trends seen for the cell surface fractions were also seen for the medium fractions. The wild type itself shed large amounts of pilus subunits into the media. The amount of shed pilin proteins remained smaller in the PilA1-ZTaq-expressing strains, further indicating that these strains had fewer or shorter pili available for shedding. Immunoblotting against $Z_{\text{Taq}}$ confirmed that PilA1-ZTaq fusion proteins were successfully incorporated into the recovered cell surface-associated pili (Fig. 3A). The correspondence of the bands on the blot with the larger expected sizes indicates that any extracellularly present PilA1-ZTaq protein was post-translationally modified, although it is not known if these modifications are the same as for native PilA1 (38–40).

For comparison of the S-layer amounts, a ΔSlp strain was included as a control to correctly identify the band belonging to Slp. However, the protein profiles for the wild-type and ΔSlp strains did not differ (Fig. 3B). This indicates that the wild-type host used in this study lacks an S-layer, probably due to the identified 76-bp deletion in the middle of its Slp gene (sll1951). For the $Z_{\text{Taq}}$-Slp strain, the larger of the expected bands, presumably corresponding to the glycosylated protein (21), was present in the cell

**FIG 3** Amounts of pilin and S-layer proteins found on the cell surface or released into the culture medium for relevant $Z_{\text{Taq}}$-displaying *Synechocystis* strains. Surface fractions from equal amounts of cells, normalized by the OD$_{730}$, and the resulting normalized amounts of culture medium were analyzed by both SDS-PAGE (top images) and immunoblotting against $Z_{\text{Taq}}$ (bottom images). Arrowheads denote expected sizes, as found for the whole-cell extract blots in Fig. 1E, for PilA1-ZTaq or $Z_{\text{Taq}}$-Slp, respectively. (A) Analysis of the recoverable pilin protein amounts for PilA1-ZTaq-expressing strains, in both wild-type and ΔpilT1 strain backgrounds. Included controls are wild-type, ΔpilA1, and ΔpilT1 strains. (B) Analysis of the recoverable S-layer protein amounts in strains expressing either $Z_{\text{Taq}}$-Slp or Slp-ZTaq. Controls included are wild-type and ΔSlp strains. For the medium fraction of $Z_{\text{Taq}}$-Slp, only one-sixth of the normalized amount was loaded due to the high protein concentration.
surface fraction. This supports the above-described immunofluorescence data (Fig. 2B and Fig. S2A) and proves that the fusion proteins could correctly cross the cell wall of Synechocystis and assemble into an S-layer on the cell surface. However, the medium fraction for the same ZTaq-Slp strain showed that large quantities of the fusion protein were also shed from the cell (Fig. 3B). Although some protein was found on the surface, the shedding suggests that anchoring of the protein was negatively affected by the N-terminal fusion of ZTaq. In contrast, the Slp-ZTaq strain had no detectable levels of extracellularly available fusion protein in the cell surface or medium fraction. This indicates that the C-terminal fusion of ZTaq instead impaired the secretion of the protein.

Regardless of the ZTaq-Slp strain being the best-performing display strain during flow cytometry (Fig. 2A), it was deemed unsuitable as a display system due to the high level of fusion protein shedding (Fig. 3B). Altogether, this meant that PIIA1-ZTaq expressed in a ΔpilT1 background was the most stable surface display system. We examined this strain for growth and pilus-mediated functions such as cell motility and transformation competency. Growth of the PIIA1-ZTaq ΔpilT1 strain was equal to the that of the wild type (Fig. S5A). Motility assays of a motile Synechocystis strain transformed to express PIIA1-ZTaq showed that this led to a loss of motility, thus exhibiting a dominant negative phenotype (Fig. S5B). The natural transformation efficiency of the PIIA1-ZTaq Synechocystis strain was also reduced; it retained less than 20% of the competency of the wild type (Fig. S5C). In summary, these results show that fusing ZTaq to PIIA1 impaired pilus-mediated functions; however, the detection of extracellular fusion proteins in pilus-like structures by immunofluorescence and in the extracted pilin fractions supports that pilus assembly was still able to progress to some degree. Comparison to the well-established Staphylococcus carnosus surface display system (43) showed that the display level for the Synechocystis PIIA1-ZTaq ΔpilT1 strain was less than half that for a ZTaq-displaying S. carnosus strain (Fig. S6) (44,45).

Quantification of the relative amounts of ZTaq fusion proteins in the sheared and shed pilus fractions from PIIA4-ZTaq Synechocystis strains. An improvement in the ZTaq display level for the PIIA4-ZTaq base strain was not realized, as was managed for PIIA1-ZTaq in this study. However, successful affibody tagging of this putative minor pilin made the various constructed strains interesting to study. The amount of pilin proteins extractable from the cells or shed into the medium was assessed as described above for the PIIA1-ZTaq strains.

For the PIIA4-ZTaq and PIIA4-ZTaq ΔpilA4 strains, smaller amounts of cell surface-associated pilins were recovered than for the wild type (Fig. 4). Immunoblotting against ZTaq showed that PIIA4-ZTaq was found among the recovered pilin proteins. The observed band corresponded to the larger of the expected sizes, indicating that the extracellularly present PIIA4-ZTaq protein was posttranslationally modified. Knockout of pilA1, creating the PIIA4-ZTaq ΔpilA1 strain, yielded no isolatable pilins or detectable PIIA4-ZTaq in either the surface or medium fraction, as expected. This supports the above-described data (Fig. 2C and D) and again suggests that the external availability of PIIA4-ZTaq depends on PilA1 due to incorporation into the type IV pili (see Fig. S4 in the supplemental material). Knockout of pilT1, creating the PIIA4-ZTaq ΔpilT1 strain, increased the amount of recovered pilins from the cells and the amounts shed into the media, as expected (Fig. 4). However, regardless of this increased pilus availability, the signal for any present PIIA4-ZTaq was reduced in the immunoblot, suggesting that its extracellular presence is also potentially associated with PilT1. In addition, the increased shedding of pili into the media for the ΔpilA4 strain indicates that PIIA4 is involved in the retraction or stability of type IV pili in Synechocystis.

Due to the presumed incorporation of PIIA4-ZTaq into the type IV pili, its effect on pilus-associated motility and transformation competency was analyzed as was done for PIIA1-ZTaq. The expression of PIIA4-ZTaq in a motile Synechocystis strain did not negatively affect motility (Fig. S5B); it was previously shown that a deletion of pilA4 has no effect on motility (23). However, the transformation efficiency of the PIIA4-ZTaq strain was reduced by more than 80% compared to the wild type (Fig. S5C).
Display of polymerizing affibodies for affinity-driven Synechocystis aggregation. Display of complex-forming affibodies on different strains of Synechocystis could be used to mediate cell-cell binding. An anti-idiotypic affibody to ZTaq (antiZTaq) has been isolated; this ZTaq:antiZTaq pair has a dissociation constant of 0.7 \( \mu M \) (46). A Synechocystis strain displaying antiZTaq was constructed by using the established display system, creating the PilA1-antiZTaq ΔpilT1 strain. Display of antiZTaq was confirmed by flow cytometry and immunofluorescence and was found be improved compared to that for the PilA1-ZTaq ΔpilT1 strain (see Fig. S7 in the supplemental material). Mixing Synechocystis strains expressing ZTaq or antiZTaq could allow cells of the different strains to bind together due to ZTaq:antiZTaq complex formation. It was hypothesized that such binding could drive floc formation and thus improve sedimentation; this could in turn benefit biomass collection.

Cell suspensions, consisting of individual strains or mixes thereof, were evaluated in terms of sedimentation speeds of the biomass. For individual strains, it was clear that the cells of all modified strains settled faster than the wild-type control (Fig. 5A). The PilA1-ZTaq and PilA1-antiZTaq strains were the quickest to settle. Deletion of pilIT1 in these strains slowed their sedimentation speeds, suggesting that the increased piliation associated with this genotype has a positive effect on cell buoyancy. Such a correlation between piliation and buoyancy was suggested in other studies previously (47, 48).

To test if a mix of ZTaq- and antiZTaq-displaying Synechocystis strains could lead to affibody-driven aggregation, the PilA1-ZTaq ΔpilT1 and PilA1-antiZTaq ΔpilT1 strains were mixed together. A mixture of the PilA1-ZTaq ΔpilT1 and PilA1-antiZTaq strains was tested in parallel as a control. For the latter pair, the two strains should not interact due to the display of the same affibody (ZTaq). Any improvement in sedimentation for this pair is rather a result of sweeping, by the fast sedimenter PilA1-ZTaq, than due to interaction. Sedimentation rates were equal for both mixtures (Fig. 5B), indicating that the interactions between ZTaq and antiZTaq were too weak or too few to induce stable floc formation. To assess if minor interactions occurred, which would not result in drastic flocculation, the above-described strain mixtures were also analyzed by phase-contrast microscopy. Samples were taken 4 h into the sedimentation test. The sizes of all aggregates in the resulting micrographs, including all single cells and multicellular aggregates, were analyzed by using Fiji (ImageJ) (49). For an example of the procedure, see Fig. S8A and S8B in the supplemental material. No significant size differences could
be observed between aggregates from the two mixtures or compared to the single strains (Fig. S8C), demonstrating a lack of specific interactions between the cells of the ZTaq and antiZTaq strains.

Previous studies have shown that the time of contact between interacting partners is an important parameter to consider (50). To test this, the PilA1-ZTaq ΔpilT1 and PilA1-antiZTaq ΔpilT1 strains were cultivated together and then analyzed for improved sedimentation, in comparison to the strains grown individually. Phase-contrast microscopy was again used to identify more discrete cell aggregation. However, no improvements in either parameter were observed (data not shown).

Display of polymerizing affibodies to mediate interspecies cell-cell binding. The display of complementary affibodies was also assessed for enabling binding between Synechocystis and the heterotrophic bacterium E. coli or S. carnosus. Both of these bacteria have established surface display systems: E. coli display is based on the adhesin involved in diffuse adherence (AIDA-I) autotransporter (45), while S. carnosus display is based on the cell wall-anchoring region of Staphylococcus aureus protein A (43, 51). The E. coli and S. carnosus display constructs contain the streptococcal protein G albumin binding domain (ABD) (5.1 kDa) and albumin binding protein (ABP) (21.8 kDa) as spacers, respectively (52). Both ABD and ABP are useful targets for fluorescein isothiocyanate (FITC)-tagged human serum albumin (HSA), to serve as a marker for the level of surface expression in these hosts (53).

E. coli strains displaying ZTaq or antiZTaq were constructed by using the AIDA-I system (45); however, a minimized version of the previously reported vector was used (54). S. carnosus strains displaying the same affibodies were received as gifts from John Löfblom (KTH School of Biotechnology, Sweden). Labeling of strains with FITC-tagged HSA showed that roughly 100% of the E. coli cells and 84% of the S. carnosus cells were labeled and thus displayed affibodies (see Fig. S9A in the supplemental material). Analysis of the subpopulations of labeled cells further showed that the level of surface expression was higher and more evenly distributed on the cells for E. coli than for S. carnosus (Fig. S9B to D).

Interactions between affibody-displaying Synechocystis and E. coli or S. carnosus displaying either ZTaq or antiZTaq was tested by incubating a mix of cells and analyzing interactions via flow cytometry. In these assays, Synechocystis was discriminated by its phycoerythrin autofluorescence (channel FL6; emission at 640 nm and excitation at 620 nm), and E. coli or S. carnosus was discriminated by being labeled with FITC-tagged HSA (channel FL1; emission at 525 nm and excitation at 488 nm). An event having fluorescence in both channels suggested a Synechocystis-E. coli or Synechocystis-S. carnosus interaction.
complex. The cytometry data were visualized in quadrant plots, where only FL6-positive events ended up in quadrant 1 (Q1), only FL1-positive events were found in Q3, and both FL6- and FL1-positive events, which indicate an interaction, were registered in Q2. Unlabeled E. coli and S. carnosus ended up in Q4. Interactions were quantified by calculating the percentage of labeled E. coli or S. carnosus cells found in Q2.

Interactions between Synechocystis and E. coli or S. carnosus expressing complementary affibodies were evident, showing that the ZTaq-antiZTaq complex could successfully form between mixed cells (Fig. 6A). The lack of an interaction with wild-type Synechocystis cells or between cells expressing the same affibody proves the specificity of binding between cells. The percentage of S. carnosus cells binding to cyanobacteria was higher than that for E. coli (Fig. 6A), even though the E. coli cells had a higher display level than S. carnosus (Fig. 5B). This could be due to the larger ABP spacer on S. carnosus, thus allowing greater accessibility to the displayed affibodies. The display level proved more important for the different Synechocystis strains. The PilA1-antiZTaq ΔpilT1 strain, which had the highest display level (Fig. 5A), also managed to bind to a higher percentage of ZTaq-displaying E. coli or S. carnosus cells than the PilA1-ZTaq ΔpilT1 strain to its counterparts (Fig. 6A). Representative quadrant plots showing successful events of binding between E. coli or S. carnosus and Synechocystis are shown in Fig. 6C and E, respectively. These plots can be compared to plots where no
interaction was evident due to wild-type *Synechocystis* being tested as an interaction partner (Fig. 6B and D).

The nature of the cell-cell binding between *Synechocystis* and *E. coli* or *S. carnosus* was further studied by microscopy. *Synechocystis* was identified by its phycocyanin autofluorescence (Texas Red filter), as in the flow cytometry analysis. The *E. coli* and *S. carnosus* strains were again labeled with FITC-tagged HSA (green fluorescent protein [GFP] filter); however, due to the uneven labeling of *S. carnosus* cells (Fig. 5D), this method of identification was used only for *E. coli* (Fig. 6F). The *S. carnosus* cells were instead identified by their smaller size and darker color in the phase-contrast images (Fig. 6G). More representative micrographs, in addition to the ones shown in Fig. 6F and G, can be seen in Fig. S10 in the supplemental material. Both large and small groups of aggregated cells could be found in the micrographs (Fig. 6F and G and Fig. S10). However, smaller groups consisting of a few cells of each microbe type predominated. The largest groups were found for binding between *Synechocystis* and *S. carnosus* (Fig. 6G and Fig. S10B), reflecting the higher level of binding for *S. carnosus* than for *E. coli* in the flow cytometry analysis. Interactions between the different species showcased a higher degree of distinctly confined species groups upon interactions with *S. carnosus* (Fig. 6G and Fig. S10B), while a higher degree of dispersal for the interacting species was seen for interactions with *E. coli* (Fig. 6F and Fig. S10A).

**DISCUSSION**

Our findings demonstrate that C-terminal fusions to the major type IV pilin protein PilA1 can be used for surface display purposes in *Synechocystis*. Display was improved by knocking out the gene encoding PilT1, the ATPase responsible for pilus retraction. This is, to our knowledge, the first example of the surface display of a heterologous protein on *Synechocystis* driven by fusion to a native surface structure. The incorporation of PilA1-ZTaq fusion proteins into the type IV pili still allowed some degree of pilus assembly; however, pilus-associated functions, such as motility and natural competency, were negatively affected. Display of proteins larger than affibodies (6.5 kDa) may not be possible since these proteins may hinder the correct assembly of the pilus. Possible limitations regarding passenger size were noted previously for surface display by fusion to pilus or fimbria subunits (55). Regardless, display by fusion to these subunits is attractive due to the high number of these structures present on the cell surface.

Complex-forming affibody pairs have recently been used to colocalize biosynthetic enzymes in metabolic pathways (56). Here, it was shown that the same principle could be applied for driving cell-cell binding. *Synechocystis* strains and *E. coli* or *S. carnosus* strains expressing complementary affibodies bound specifically to each other. This has implications for future photosynthetic microbial communities. One such application could be to physically bind heterotrophs to cyanobacteria that have been modified to produce and secrete feedstocks such as sugars (57), acetate (3), or glycerol (58). This forced proximity could allow a more efficient chemical transfer between microbes than what could be realized in a free-floating setup. Similar interspecies binding between FLAG-displaying *S. elongatus* and protein A-displaying *S. cerevisiae* has also been shown (17). However, in that system, an externally added antibody was necessary to bring the cells together. Attachment between the cyanobacterium *Microcystis aeruginosa* and an *E. coli* strain engineered to display a cyanobacterial lectin has also been described (59).

The inability to induce flocculation and improve sedimentation for a mixture of *Synechocystis* strains displaying complementary affibodies could be because the display level of the ZTaq:antiZTaq complex was not high enough to drive cell-cell binding. The display level for the PilA1-ZTaq ΔpilT1 *Synechocystis* strain was shown to be less than half that for the ZTaq display in *S. carnosus*; additionally, the *E. coli* AIDA-I system was previously shown to outperform affibody display in *S. carnosus* (45). This could explain why interspecies *Synechocystis* binding did not occur, while interspecies binding with either *E. coli* or *S. carnosus* was possible. An improved display level in combination with other higher-affinity binding pairs could potentially overcome this. However, all tested
modified Synechocystis strains sedimented faster than the wild type. This could be due to the observed reduction in extractable pili from these strains and the potentially truncated nature of these pili due to the incorporation of fusion proteins. A positive correlation between cyanobacterial buoyancy and the presence and amount of pili was speculated previously (47, 48). The type IV pili in Synechocystis are also known to be glycosylated (39); such extracellular polysaccharides contribute to the overall negative charge of the cells, which allows them to remain in suspension (60). Reduced piliation of the cells would therefore also reduce the quantity of extracellular polysaccharides, possibly affecting the ability of the cells to remain suspended. The altered properties of the pili due to the incorporation of affibodies could also have played a role in affecting the buoyancy of the cells.

The described PilA1 display system in Synechocystis could also be extended to display peptides with affinities for different types of materials (61, 62), facilitating, e.g., cell immobilization. This could aid in the use of cyanobacteria in large-scale processes.

Our results can also be used to further understand the type IV pili in Synechocystis. The location and function of the putative minor pilin PilA4 in Synechocystis are, to our knowledge, so far unknown. Previous studies have shown that PilA4 is not essential for type IV pilus-driven motility in Synechocystis (23), and here, the expression of PilA4-Z_Taq did not affect motility. Its function as a carrier protein in this study shows that PilA4 locates to the surface of the cell. The inability of PilA4-Z_Taq to mediate display in a pilA1 knockout strain, in addition to several instances of fluorescence being seen in pilus-like structures in immunofluorescence micrographs, further suggests that it is incorporated into the pilus. Knockout of the pilus retraction ATPase (pilT1) increased the display efficiency for PilA1-Z_Taq but caused an unexpected loss of display in the PilA4-Z_Taq strain. These contrasting results suggest divergent regulation or a different role for PilA4 than for PilA1. The reduced relative quantity of PilA4-Z_Taq in the pilin fraction upon PilT1 deletion, as well as the increased shedding of pilins in a ΔpilA4 strain, indicates that PilA4 is a minor pilin involved in pilus retraction or stability while not being strictly required for pilus synthesis. However, more detailed studies are required in order to confidently confirm these suggestions. Minor pilins of type IV pilus systems in other organisms, such as P. aeruginosa and Neisseria spp., have mainly been implicated in priming the pilus for assembly rather than retraction (63–66). However, in the simpler Vibrio cholerae type IV pilus system, a minor pilin (TcpB) has been shown to act in both the assembly and retraction of pili (67). Similar affibody tagging of other putative minor pilins in Synechocystis could help elucidate their localization as well. For the other putative pilin included in this study, PilA2, immunofluorescence for the PilA2-Z_Taq protein was found to be located at the cell surface, indicating that this is the native location of PilA2. It is also important to note that the main Synechocystis host used in this study is nonmotile due to a mutation in the spkA gene (68). The characteristics of the pili for this nonmotile host could be different from those for a motile strain; reduced piliation for a nonmotile glucose-tolerant strain was noted previously (69). These possible differences mean that the above-noted results for the putative minor pilins may be different in the presence of a fully functional type IV pilus system.

Our results also clarify some aspects of the protein constituent of the Synechocystis S-layer. Blocking the C terminus of Slp by fusion to Z_Taq to a large extent hindered the correct secretion of the protein, supporting the notion that Slp carries a noncleavable C-terminal secretion signal, as was proposed previously (32, 34). In addition, fusion of Z_Taq to its N terminus allowed secretion and assembly into an S-layer but also resulted in excessive shedding of the fusion protein into the culture medium. This indicates that the region responsible for the surface anchoring of Slp is located in the N-terminal part of the protein. These effects have also been observed when the S-layer protein (RsaA) in Caulobacter crescentus was used for the surface display of fused peptides (70). The ability to identify permissive sites within RsaA, suitable for the surface display of passengers of various sizes (71), indicates that the same could be done for Slp from Synechocystis.

In conclusion, this work demonstrates the ability to successfully display an affibody
passenger protein on the cell surface of *Synechocystis* by fusion to PilA1, the major pilin protein of the native type IV pili. Affibody-displaying *Synechocystis* strains were able to bind by protein complex formation to *E. coli* or *S. camosus* strains displaying the anti-idiotypic affibodies. These results have implications for the development of methods that would enable the immobilization of *Synechocystis* onto surfaces or other microbes in engineered microbial consortia. In addition, the putative minor pilin PilA4 was shown to localize to the cell surface in a presumably type IV pilus-dependent manner, and the protein domains responsible for the secretion and anchoring of the S-layer protein in *Synechocystis* were proposed to be located at the C and N termini, respectively.

**MATERIALS AND METHODS**

**Culture conditions.** Wild-type *Synechocystis* sp. strain PCC 6803 (a gift from Martin Fulda, University of Gottingen, Germany) used in this study is a nonmotile GT-S derivative. *Synechocystis* strains were cultivated in BG11 medium buffered to pH 7.9 with 25 mM HEPES. Cultures were grown in a climatic chamber (catalog number SE-1100; Percival Climatics) at 30°C with 20 μE/m²s illumination and 1% (vol/vol) CO₂. For growth on solid medium, 1.5% (wt/vol) agar and 0.3% (wt/vol) sodium thiosulfate were added to BG11 medium. When needed, antibiotics were added (50 μg/ml kanamycin, 25 μg/ml chloramphenicol, and 50 μg/ml spectinomycin). Unless noted otherwise, cells were cultivated in 24-deep-well plates on a Multi-Genie microplate shaker. The plates were sealed by using sterile gas-permeable adhesive seals. The sides of the plates were covered with aluminum foil to allow equal light supply, from above, to all wells. Growth was monitored by measuring the optical density at 730 nm (OD₇₃₀).

*S. camosus* strains (gifts from John Löfblom, KTH School of Biotechnology, Sweden) and *E. coli* strains were cultivated at 37°C in chloramphenicol-supplemented B2 and LB media, respectively.

**Plasmid and strain construction.** All strains and plasmids used in this study are described in Table 1. All primers are listed in Table S1 in the supplemental material.

The replicative plasmid pJA2 was used for expressing fusion proteins in *Synechocystis* under the control of the Pₚmaa promoter (30). This replicative plasmid originates from the pPMQAK1 vector constructed previously by Huang et al. (72), which was subsequently modified by Anfert et al. (26). To prepare the pJA2 backbone, it was PCR amplified, treated with DpnI, digested with XbaI and PstI (or AvrII and SpeI), and subjected to FastAP thermosensitive alkaline phosphatase.

Amplification of affibody genes (see the supplemental material for sequences) and carrier protein genes was done by introducing a flexible linker region (GSSSGSS) and restriction enzyme sites at either end. pilA1 (sll1694), pilA2 (sll1695), pilA4 (sll1456), and the S-layer protein gene (sll1951) were amplified from purified *Synechocystis* genomic DNA. Amplification of sll1951 required touchdown PCR (73). The fusion protein genes were constructed with overlap PCR, where the complementary linker sequence was used to enable fragment fusion. Cloning into the pJA2 vector was achieved via restriction enzyme digestion, ligation, and subcloning into *E. coli*.

The antigen 43 autotransporter construct required amplification of the signal peptide (amino acids 1 to 52) and β-chain translocator domain (amino acids 552 to 1039) from the *flu* gene of *E. coli* Top10. The affibody gene was fused to the β-chain domain fragment via overlap PCR. The signal peptide was added by subcloning in *E. coli*. The full insert was finally cloned into the pJA2 backbone.

The Golden Gate method (74), using the GeneArt TypeIIs assembly kit (AarI), was used to construct suicide vectors for creating gene knockouts in *Synechocystis*.

The constructed replicative pJA2 plasmids were transformed into *Synechocystis* by electroporation. Suicide vectors were transformed into *Synechocystis* by natural transformation (75).

To enable AIDA-I-driven surface display of affibodies in *E. coli*, a minimized variant of the previously described pAraBAD-Z-EC vector (45), here called pAraBADMin, was used (this was a gift from Ken Andersson, KTH School of Biotechnology, Sweden). This variant has been minimized by 338 amino acids, mainly by exchanging the albumin binding protein for a smaller albumin binding domain and shortening the linker region between the passenger and the AIDA-I β-domain (54). This vector was digested with Xhol and SpeI, and equally digested affibody fragments were ligated into the backbone. Expression was done by using the *E. coli* BL21(DE3) strain.

*Synechocystis* cell lysis and immunoblotting against affibody fusion proteins. Ten milliliters of cultures at an OD₅₇₀ of 1 to 2 was pelleted and lysed in 400 μl lysis buffer consisting of 50 mM Tris-HCl, 150 mM NaCl, 1% Triton X-100, 1 mg/ml lysozyme, and complete EDTA-free protease inhibitor (Roche). The cells were incubated for 30 min at 37°C. Subsequently, 100 μl acid-washed glass beads was added, and bead beating was performed by vigorous shaking for 20 min at 4°C. Lysates were collected by centrifugation. Twenty micrograms of total protein per sample was analyzed by using SDS-PAGE, by transfer onto a 0.45-μm polyvinylidene difluoride (PVDF) membrane. Immunoblotting was done by using all solutions, except for the secondary antibody, provided in the WesternBreeze chromogenic kit. As a primary antibody, a goat antiaffibody antibody (Affibody AB) was used at 0.1 μg/ml. A secondary anti-goat alkaline phosphatase-conjugated antibody (catalog number A4187; Sigma) was used at a 1:10,000 dilution.

Prediction of signal peptides was done for all carriers and taken into account when calculating expected protein sizes. PILFIND 1.0 (76) was used for PilA1, PilA2, and PilA4. No cleavable signal peptide was detected for the S-layer protein. The signal peptide for *E. coli* antigen 43 is known (77).
Flow cytometry to assess affibody surface display on Synechocystis. Cells were analyzed after 50 h of growth, at an OD_{730} of 2.5 to 3. Fifty microliters of each culture was pelleted, and the cells were washed twice with PBS-P (phosphate-buffered saline supplemented with 0.1% [wt/vol] Pluronic-F108NF [BASF Corporation, Mount Olive, NJ]). Cells were resuspended in 100 μl PBS-P containing 0.5 μg/ml goat anti-affibody antibody (Affibody AB). Incubation was done at room temperature (RT) with slow mixing for 1 h. Afterwards, cells were pelleted, washed once in PBS-P, and then resuspended in 100 μl PBS-P containing 0.5 μg/ml anti-goat Alexa Fluor 488-conjugated antibody (Life Technologies). Incubation was carried out in the dark for 1 h on ice. Cells were again pelleted and washed once in PBS-P. Finally, the cells were resuspended in PBS-P, and fluorescence was measured by flow cytometry (Beckman Gallios; Beckman Coulter) using channel FL1 (emission at 525 nm and excitation at 488 nm). A total of 10,000 events were acquired. Data analysis was done by using FlowJo (FlowJo LLC). The cell population was gated based on the samples' front-scatter (FSC)-versus-side-scatter (SSC) dot plot. The gated cells were analyzed for their median fluorescence intensity (MFI) within the FL1 channel. All mutant strain MFI values were normalized against the MFI measured for the wild-type control in each run; the results are thus presented as relative values.

Relative quantification of pilus and S-layer protein amounts on the cell surface and in culture media. Synechocystis strains were grown in shake flasks until the OD_{730} reached ~2. Normalized amounts, by using the OD_{730} values, were pelleted; 50 ml was used for the most-dilute culture. Both the cell pellet and resulting culture medium were saved for further treatment.

For analysis of proteins in the culture medium, an adjusted version of a previously reported protocol was used (25). The medium was centrifuged three times to ensure the full removal of cells. Proteins were precipitated by the addition of trichloroacetic acid to a final concentration of 10% (wt/vol), incubation on ice for 2 h, and centrifugation for 15 min at 4°C. The protein pellet was washed twice in cold 90% acetone, dried, and resuspended in 1× loading buffer.

For the isolation of pili, the cell pellet was resuspended in 0.5 ml BG11 medium and vortexed for 5 min on the maximum setting. The suspension was centrifugated at 13,000 × g; this was repeated twice to fully remove all cells. The collected liquid fraction was further precipitated with trichloroacetic acid as described above for the culture medium. This protocol was adjusted from a previously described one (78).

For the isolation of S-layer proteins, the cell pellet was first washed in BG11 medium and then resuspended in 200 μl 10 mM HEPES containing 10 mM EGTA (pH 7.7) and incubated for 30 min at RT. Afterwards, the samples were vortexed for 2 min. The collected suspension was centrifuged at 13,000 × g; this was repeated twice to fully remove all cells. This protocol was adjusted from a previously described one (79).

SDS-PAGE and immunoblotting (see above for details) were performed on equal amounts of isolated fractions from all strains. The only exception to this was for the medium fraction from the E. coli Sip strain, where only one-sixth of the amount was loaded.

Sedimentation assay of affibody-displaying Synechocystis. Cultures grown for 48 h, reaching an OD_{730} of ~2, were pelleted and resuspended in fresh BG11 medium to reach an OD_{730} of 2.5. Cells were transferred, as either single strains or a 1:1 mix of two strains, into glass tubes. Sedimentation rates were estimated by continuously measuring the OD_{730} of the topmost layer of the cell suspension.

Binding assay for affibody-displaying Synechocystis and S. carnosus or E. coli. Cultures of affibody-displaying E. coli grown overnight were diluted 100-fold into fresh LB medium and allowed to grow at 37°C until an OD_{600} of 0.5 was reached. Expression of the AIDA-I–affibody constructs was induced with 0.6% L-arabinose and subsequent cultivation for 3 h at 30°C (45). Affibody-displaying S. carnosus did not require induction. A total of 7.5 μl of S. carnosus cultures grown overnight or induced E. coli cultures grown as described above was taken for each sample. The cells were washed twice in PBS-P and labeled by incubation in PBS-P containing 225 nM FITC-labeled human serum albumin (HSA) for 1 h on ice. The cells were washed once after labeling in PBS-P. FITC-labeled HSA was prepared by labeling HSA using the Pierce NHS-fluorescein antibody labeling kit (Thermo Scientific) according to the supplier’s recommendations.

To prepare the cyanobacterial cells, 50 μl of culture reaching an OD_{730} of ~3 was taken for each sample. The cells were washed twice in PBS-P.

The interaction assay mixtures were prepared by mixing washed Synechocystis cells and FITC-labeled S. carnosus or E. coli cells at a roughly equal ratio, to a total volume of 100 μl. The mixtures were incubated on ice for 2 h. Flow cytometry analysis was preceded by gently suspending the mixtures in PBS-P. Flow cytometry (Beckman Gallios; Beckman Coulter) analysis was done by registering events in channels FL1 (emission at 525 nm and excitation at 488 nm) and FL6 (emission at 640 nm and excitation at 620 nm). A total of 35,000 events were acquired. Data analysis was done by using FlowJo (FlowJo LLC). The cell populations were gated based on the samples’ FSC-versus-SSC dot plots. The gated cells were analyzed in quadrant plots, where the signals obtained in channels FL6 (phycocyanin) and FL1 (FITC) were plotted for each event.

Microscopy and image analysis. Cells analyzed for the surface display of affibodies or interspecies cell-cell binding were prepared in the same manner as described above for flow cytometry analysis. Samples for analysis of intraspecies cyanobacterial binding were taken 4 h into the sedimentation test, done as described above. All samples were mounted onto 1% agarose pads prior to analysis. The mounted samples for the inter- and intraspecies binding tests were highly diluted to ensure that any observed aggregates were due to binding rather than a too-concentrated sample. A Ti Eclipse inverted research microscope (Nikon) with a ×100/1.45 numerical-aperture (NA) objective (Nikon) was used to obtain phase-contrast and fluorescence images (GFP and Texas Red filters). Fiji (ImageJ) was used for image processing and analysis (49).

For the evaluation of intraspecies cyanobacterial binding, large-scale phase-contrast images were acquired by using the image stitching function of NIS-Elements microscopy software. These micrographs
were treated in Fiji with the “analyze particles” function to measure the size of all present aggregates, including single cells and multicellular aggregates. All noncell targets included by the software in the resulting data were manually removed.

SUPPLEMENTAL MATERIAL

Supplemental material for this article may be found at https://doi.org/10.1128/JB.00270-18.

SUPPLEMENTAL FILE 1, PDF file, 7.1 MB.

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We declare no conflicts of interest.

REFERENCES


